Muscles Alive

Second Edition

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THEIR FUNCTIONS REVEALED
BY ELECTROMYOGRAPHY

J. V. Basmajian, M.D.

PROFESSOR AND HEAD OF THE DEPARTMENT OF ANATOMY,
QUEEN'S UNIVERSITY, KINGSTON, ONTARIO, CANADA.

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Preface to the Second Edition

When the first edition of *Muscles Alive* appeared some four or five years ago, even I (who obviously had the greatest hopes for it) was surprised by the favorable response from both reviewers and readers. Thoroughly warned that works of this nature have few readers and fewer buyers, everyone was prepared for only a modest response. Yet the publishers, in a moment of omniscient optimism, printed an unusually large run of copies. Thus few people could have predicted that a second edition would be justified for many years to come.

The supply of copies kept shrinking at a brisk rate. Now the happy problem that faced us was whether to prepare a completely new edition rather than to reprint the first. Because I had gathered a great deal of new material, and even though the book would remain "out of print" for some months, we agreed that a new edition was the answer.

This is a new edition in what I hope is the best sense. What was good and true in the first edition has been retained and will be obvious to old friends. What was shown to be false or outmoded—even in four years—has been replaced with newer material. Whole new sections and chapters have been written based on recent findings and trends in electromyography. The chapters have increased from 13 to 19 (plus an Appendix) and the pages by similar proportions. The illustrations have increased by 36 and the references have more than doubled.

Electromyography has regained its vitality and vigour in this decade and has given birth to a great many important findings and to the new technology of myoelectric controls for man-

machine complexes. Indeed, I have found it a challenge to keep up with the many developments elsewhere. Thus, I must apologize to any groups who find that I have missed their work and I welcome their sending me reprints and references.

This is a scientific book without apology for being scientific. Yet I have tried to avoid making it dull as, alas, most scientific books tend to be. I have tried to retain the simple style of the first edition which received widespread approval, using a minimum of pretentious jargon. The subject of electromyography is too important for it to be allowed to become dull.

Because this preface is meant to supplement rather than to replace, the preface to the 1st edition is printed in full in the following pages. The purpose and hopes expressed there remain unchanged and paramount in my thinking. One might add that this 2nd edition appears on the hundredth anniversary of the publication of Duchenne's *Physiology of Motion*, reminding us again of our great debt to that immortal work.

Queen's University   J. V. B
1967

Preface to First Edition

Almost a hundred years ago, Duchenne concluded the preface of his epoch-making *Physiology of Motion* with the remark that after ten years of continuous research his task was completed with the writing of his book. After a similar period of some ten years of intense research on muscle function by a modern electronic technique that Duchenne himself would have enthusiastically employed, I have brought together into this book my own findings and those of many others from all over the world. Pleased as I am to be completing my present toil, my main feeling is one of renewed and profound admiration for the old master who, single-handed and against considerable opposition, produced a work that has stoutly withstood a century's buffeting. True, many modifications of his teaching have been dictated by clinical observations (particularly by Beevor) and by the electromyographic findings to be described in this volume. What impresses me most, however, is that this book will in no way replace or even subordinate his. On the contrary, it will complement and illuminate it as did Beevor's Croonian Lectures *On Muscular Movement* to the Royal College of Physicians of London in 1903. I would like to hope, then, that this work will be accepted kindly as the direct and vigorous lineal descendant of the works of Duchenne and Beevor.

In particular, this book is intended for all those who deal with living muscles and movement, and I have consciously tried to make it indispensable for such workers. These include physiologists, zoologists, and anatomists, and their students; orthopedic surgeons, kinesiologists, physical medicine specialists and thera-

pists; neurologists; and physical educationists. Indeed, it is diffi-
cult to stop the list there because the chapter on normal pharyn-
geal and laryngeal muscles and another on eye muscles will be of
special interest to specialists in those fields. Such chapters were
especially meant to be comprehensible to ordinary scientific
readers as well.

Finally, it is my fond hope that the reader will soon discover
that this book is not just another treatise on standard kinesiology,
a subject that is already quite adequately dealt with by an im-
pressive (and sometimes oppressive) series of books. Nonetheless,
the informed reader will soon detect that it includes a great deal
of both old and new information that rightfully belongs in stand-
ard kinesiology textbooks but which has not been generally
available to their authors.

Acknowledgments

The author of any book of this type owes a great deal of gratitude to many people. Friends, colleagues and assistants have all contributed, sometimes quite unawares, to this publication. First contributing to its initiation through their inspiration for research and then to the pursuit of research through practical help and direct encouragement, they finally forced me into the actual writing of this book. To them all I am truly grateful—not the least to my good friend Otto Mortensen of the University of Wisconsin who added the final straw by his authoritative insistence that I *must* write it.

Through the years and sometimes at critical periods the following friends and colleagues have made my researches possible: J. C. B. Grant (first my teacher and then, until his retirement, my "chief"), R. G. MacKenzie, W. A. Hawke, W. T. Mustard, A. W. Ham and A. N. Mitchell. My association with Philippe Bauwens at St. Thomas's Hospital in London during 1953 (after a number of years of unguided floundering) was not only a turning point in my electromyographic work, but it was also a most pleasant experience which has become a cherished memory.

Many of my individual research projects, although they have never been large and stultifying "team-efforts," nonetheless have been carried out cooperatively with one or two colleagues and graduate students. Where publications have resulted, these are noted in suitable parts of the text and in the list of references, but here I must thank in particular the following persons: J. F. Murray (my first and perhaps most stimulating companion-in-research), Johanna W. Bentzon, W. B. Spring, Abdul Latif, Robert Boyko, Alex Szatmari, Wilma E. K. Brown, Rita M.

Harland, H. J. Lawrence, R. S. Lewis, F. J. Bazant, Anthony Travill, C. R. Dutta, G. M. Lyons, M. D. Low, G. A. Stecko, W. J. Forrest, M. Baeza, C. Fabrigar, T. G. Simard and V. Janda.

My debt is immeasurable to the following associates and assistants in electronics: Peter Stiles, William Forde, R. J. Black and Glenn Shine. The valuable assistance of various undergraduates has generally gone unheralded. Nevertheless it has been deeply appreciated. I regret that I cannot list the names of the hundreds who have acted as our "guinea pigs."

Electronic research on a large scale is expensive. Ours has been generously supported at various times by the following organizations: Bickell Foundation, Banting Research Foundation, Muscular Dystrophy Association of Canada, Medical Research Council of Canada, Rehabilitation Foundation for Poliomyelitics and Orthopedically Disabled ("March of Dimes"), Alcoholism Research Foundation, Poulenc, Ltd. (Montreal), Lederle Company, and Stanley Cox, Ltd., of London (which build expensive apparatus at cost), the University of Toronto and Queen's University.

Many authors have been drawn upon freely. In quoting them, I hope that I have not misrepresented their views. Many are personal friends and acquaintances and have helped me through their letters and conversations. I have also used a substantial number of illustrations from the works of others. Permissions for reproduction have been obtained from the publishers or editors and the sources are individually indicated in their proper places.
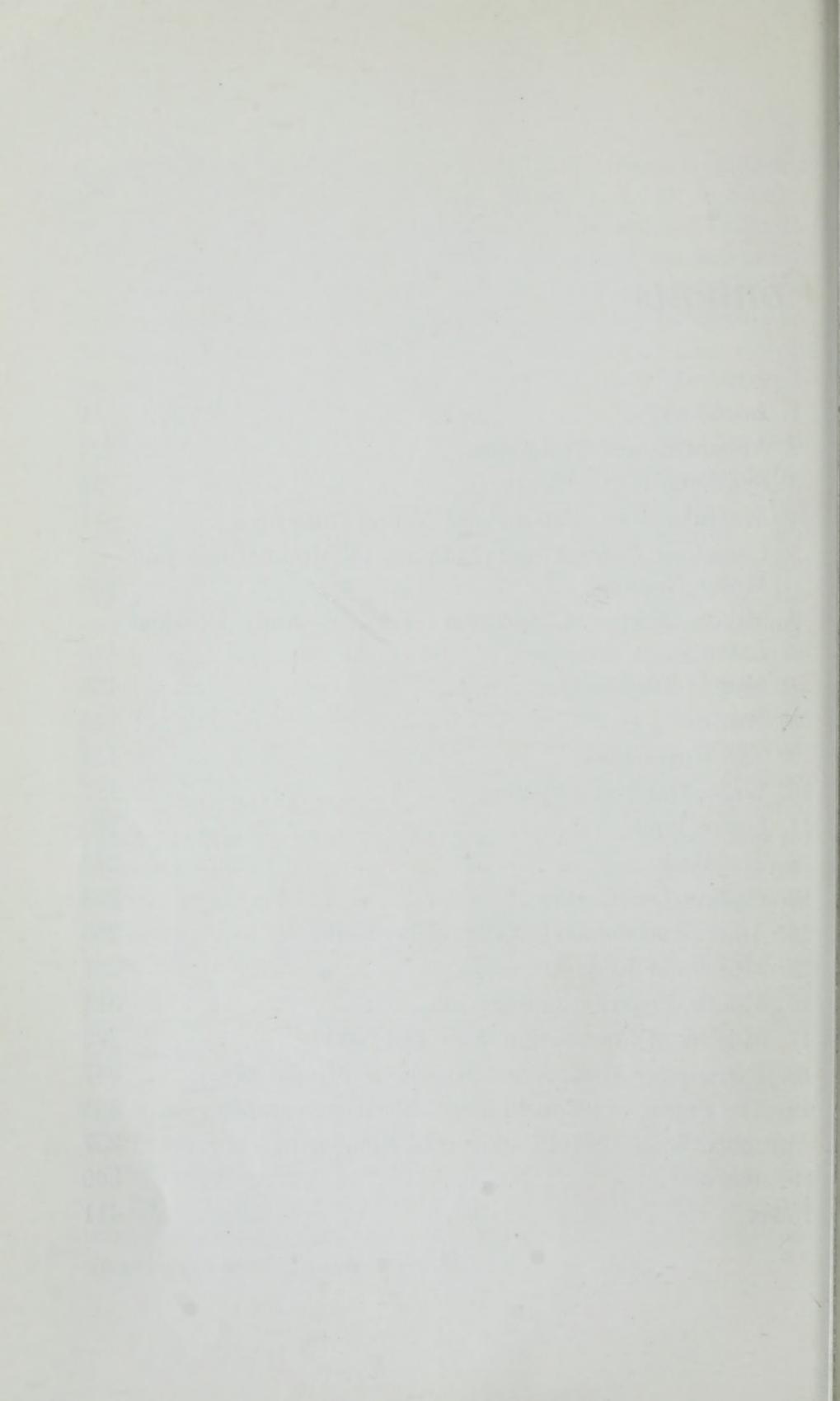
During the preparation of the first edition, the help of my junior colleagues Anthony Travill and G. M. Lyons in the critical reading of the entire manuscript greatly improved the finished product; so, too, the work of Glenn Shine has improved both first and second editions.

I am especially happy to acknowledge and include the work of my distinguished friend, Professor A. D. Moore, who wrote the text of what has become Chapter 3.

The enduring tolerance and active assistance of my wife, the unstinting attention to detail of my secretary, and the pleasant relationships throughout with my publishers have all made continued work on this book a pleasure.

Contents

Introduction

Ｉnherent movement is the prime sign of animal life. For this and many other reasons, man has shown a perpetual curiosity about the organs of locomotion in his own body and in those of other creatures. Indeed, some of the earliest scientific experiments known to us concerned muscle and its functions.

With the reawakening of science during the Renaissance, interest in muscles was inevitable. Leonardo da Vinci, for example, devoted much of his thought to the analysis of muscles and their functions. So, too, did the acknowledged "father" of modern anatomy, Andreas Vesalius, whose influence through his monumental work, the "Fabrica," extends down to this day. In one sense, however, the heritage of Vesalius was unfortunate because it stressed the appearance and the geography of dead muscles rather than their dynamics (fig. 1). During the subsequent years, the first scientist to give life back to the muscles was Galvani who at the end of the eighteenth century reported his epoch-making experiments with nerve-muscle preparations and animal electricity (fig. 2). For more than two centuries, then, biologists have known and acted on Galvani's revelation that skeletal muscles will contract when stimulated electrically and, conversely, that
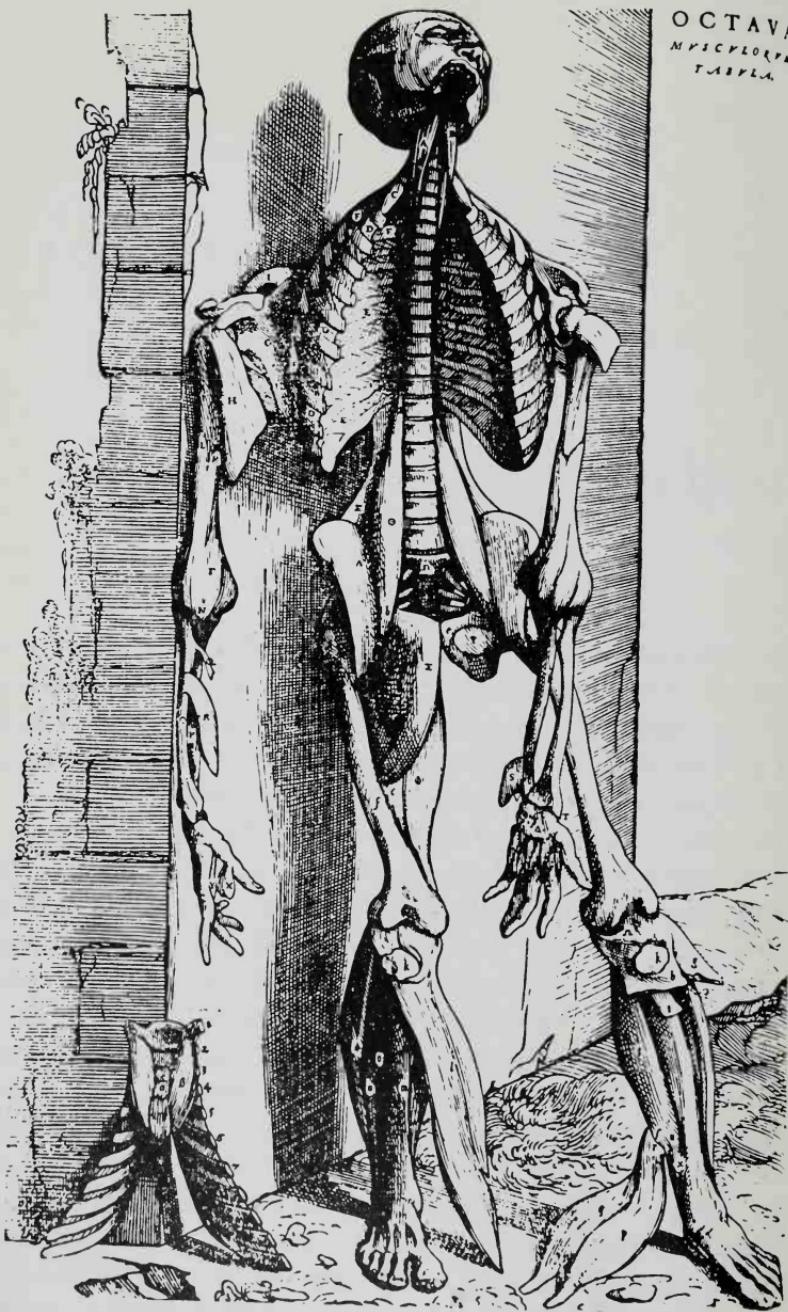
FIG. 1. A "muscle-man" from Vesalius' *Fabrica*. (Reproduced by permission from a rare 1555 edition in the Library of Queen's University.)
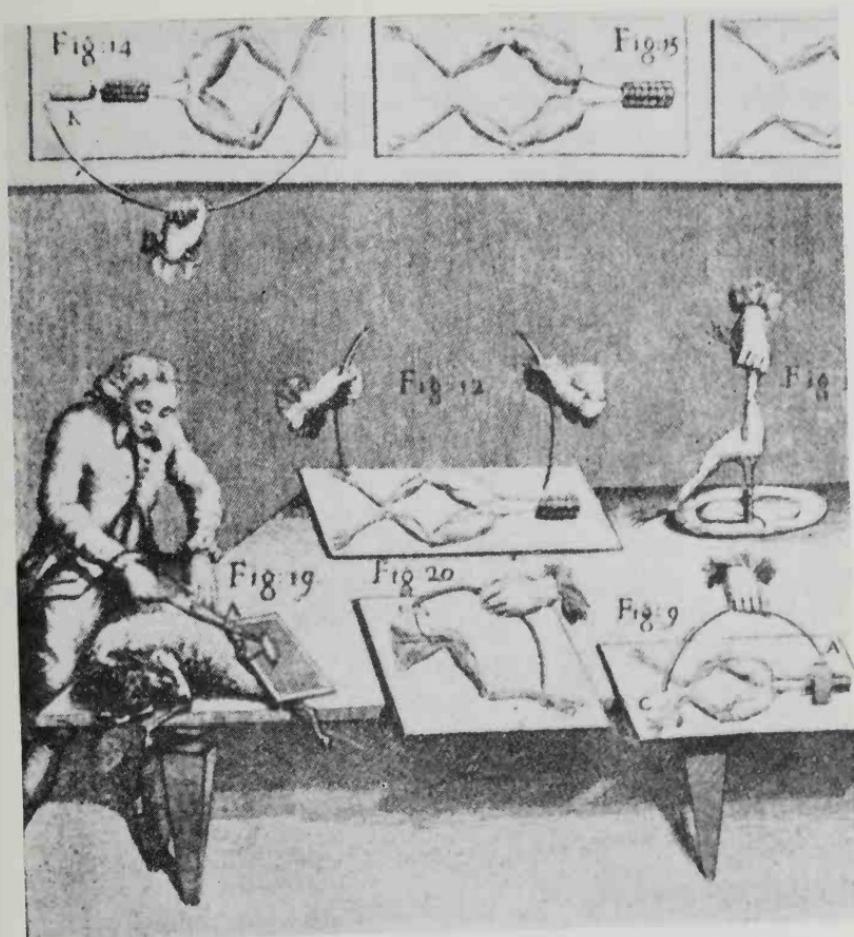
FIG. 2. Galvani's demonstrations of the effects of electricity on muscles of frogs and sheep. (From Fulton's reproduction of a plate in Galvani's *De viribus electricitatis in motu musculari commentarius*, 1792.)

they produce a detectable current or voltage when they contract from any cause.

Of course Galvani's findings formed the beginning of neurophysiology and the study of the dynamics of muscular contraction, but the world had to wait for the Frenchman, Duchenne, in the middle of the past century, to apply the use of electricity for the systematic determination of the dynamics of intact skeletal

muscles (fig. 3). His immortal work, *Physiologie des mouvements*, is now, fortunately, available again in a new English edition (translation by E. B. Kaplan). It was based on numerous studies of the movements produced by muscles that were stimulated through the skin by electric currents (fig. 4). No one before or after has contributed so much to our understanding of muscular function, although Beevor's (1903) contributions cannot be ignored.

In this introductory chapter, I have studiously avoided a general discourse on the history of muscle function that dates back to Aristotle and Galen and runs through Galileo, Borelli, Volta, Du Bois Raymond and others, because the facts are now freely available in other books. Particularly useful and readable is the

Fig. 3. G. B. Duchenne, father of medical electrophysiology

historical account given by Rasch and Burke in their recently
published textbook (1963) which has a wide distribution.

The second aspect of Galvani's discovery, namely, that muscles
produce electricity, proved to be largely a scientific curiosity until
the twentieth century when improved methods of detecting and
recording minute electrical discharges became widely available.
The main (though certainly not sole) credit for launching almost
40 years ago the new technique that deals with electrical poten-
tials produced by muscle—or electromyography—must go to the
English physiologists, Adrian and Bronk, to D. Denny-Brown
and to several Scandinavians. Being neurophysiologists, these
men and their colleagues did not concern themselves with the
use of the new techniques for unravelling the functions of indi-
vidual muscles and groups of muscles. Moreover, it must be ad-
mitted that the earliest techniques were really not appropriate
for such detailed studies. For two decades, whenever electro-

Fig. 4. Duchenne's illustration of electrical stimulation of muscles

myography was applied to man it was more for diagnostic and clinical reasons than for basic kinesiology.

Toward the end of the Second World War, with a marked improvement of electronic apparatus and the increasing availability of such tools, anatomists, kinesiologists and orthopedic surgeons began to make increasing use of electromyography. The first study that gained wide acceptance was that of Inman, Saunders and Abbott (1944) who reported their work on the movements of the shoulder region.

During the decade of the fifties, electromyography for anatomical studies became widespread. Frequent reports from American, British, Canadian, Scandinavian, French and German sources became commonplace in the literature. It may be noted, however, that most papers on human electromyography are purely clinical and those on the functional aspects of muscles are scattered here and there in many hundreds of journals in a dozen different languages. This has made the job of anatomy textbook writers and editors most difficult and, apparently, sometimes overwhelming. As a result, many of the newer findings are not reaching the textbooks, particularly those findings that are reported in obscure journals. To a large extent, that very fact led to the writing of the first edition of this book.

In his book, Duchenne freely admitted that localized faradization of muscles by his technique was "insufficient to throw light on the physiology of voluntary motion" because "isolated action of the muscle is not in the nature of things." To overcome this inherent defect in his technique, Duchenne supplemented it with many clinical observations. His conclusions form the basis of all our textbook descriptions of muscle action, but they are not dogma. I am certain that Duchenne himself would have enthusiastically embraced the technique of electromyography if he were alive today.

Basis of Electromyography

The Motor Unit

Unless the reader has a knowledge of the structural and functional units in striated muscles, he will not appreciate fully much

of the literature in electromyography. The structural unit of contraction is, as everyone knows, the muscle cell or muscle fibre (fig. 5). Best described as a very fine thread, this muscle fibre has a length of up to 30 mm but is less than 100 μ (or 0.1 mm) wide. On contracting it will shorten to about 57% of its resting length (Haines, 1932, 1934).

By looking at the intact normal muscle during contraction one would believe, quite erroneously, that all the muscle fibres were in some sort of continuous smooth shortening. In fact, this is not true; instead there is a virtual buzzing of activity in which the fibres are undergoing very rapid changes. The apparently smooth contraction is a summation of all these rapid changes (to be described below).

In normal mammalian skeletal muscle, the fibres probably never contract as individuals. Instead, small groups of them contract at the same moment. On investigation, one finds that all the members of each of these groups of muscle fibres are supplied
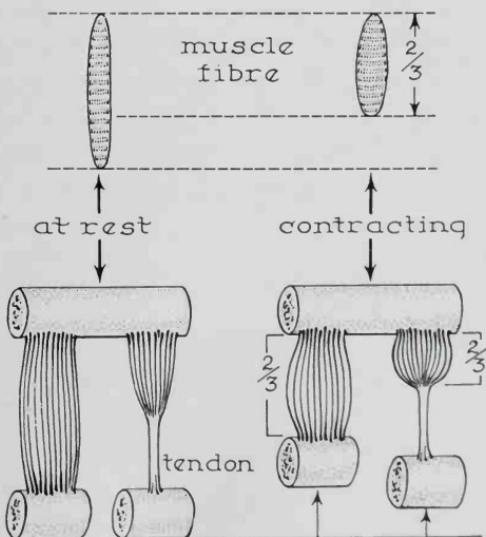
Fig. 5. The structural unit of contraction is the muscle fibre. The greatest amount a whole muscle can actively shorten is dependent on the maximum contraction of its contractile units. (From Basmajian, 1960.)

by the terminal branches of one nerve fibre or axon whose cell body is in the anterior horn of the spinal grey matter. Now, this nerve cell body, plus the long axon running down the motor nerve, plus its terminal branches and all the muscle fibres supplied by these branches, together constitute a motor unit (fig. 6). The motor unit is, then, the functional unit of striated muscle, since an impulse descending the nerve axon causes all the muscle fibres in one motor unit to contract almost simultaneously.

Motor units normally contract sharply upon the arrival of such nervous impulses at various frequencies, usually below 50 per second. This frequency seems to be the upper physiological limit for the frequency of propagation of axonal impulses and, apparently, such factors as a necessary recovery period and the threshold of fatigue in nerves and muscle must be involved in deter-
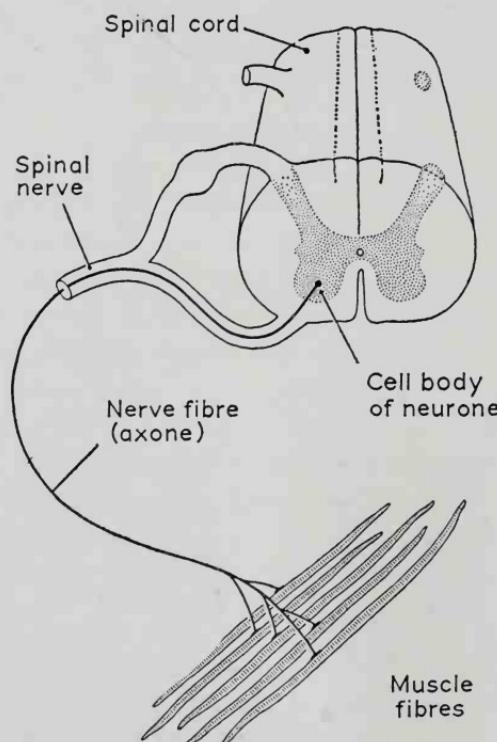

Fig. 6. Scheme of a motor unit. (After Basmajian, 1955a.)

mining it. As interesting as this matter is, it must be postponed to a later chapter (p. 76).

The number of muscle fibres that are served by one axon, i.e., the number in a motor unit, varies widely, but certain rules have been established in recent years. Generally, it has been agreed that muscles controlling fine movements and adjustments (such as those attached to the ossicles of the ear and to the eyeball and the larynx) have the smallest number of muscle fibres per motor unit. On the other hand, large coarse-acting muscles, e.g., those in the limbs, have larger motor units. The muscles that move the eye have small motor units with less than 10 fibres per unit, as do the human tensor tympani muscle of the middle ear, the laryngeal muscles and the pharyngeal muscles. These are all rather small delicate muscles which apparently control fine or delicate movements.

Krnjević and Miledi (1958) report 7 to 17 fibres per motor unit in the rat diaphragm, which suggests that this muscle, too, has a fine or delicate control. The size of motor units in the rabbit pharyngeal muscles is also quite small—ranging from as few as two to a maximum of only six (Dutta and Basmajian, 1960). The size of the motor units in our study was determined by tracing the individual nerve fibres along their final distribution to the muscle fibres (figs. 7 and 8). Other observers have calculated the total number of muscle fibres in a muscle and the total number of nerve fibres in its motor nerve. Then, by dividing the former by the
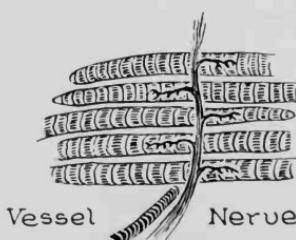

Fig. 7. Drawing of a nerve bundle ending on muscle fibres—teased specimen (low power, phase contrast microscope). (From Dutta and Basmajian, 1960.)
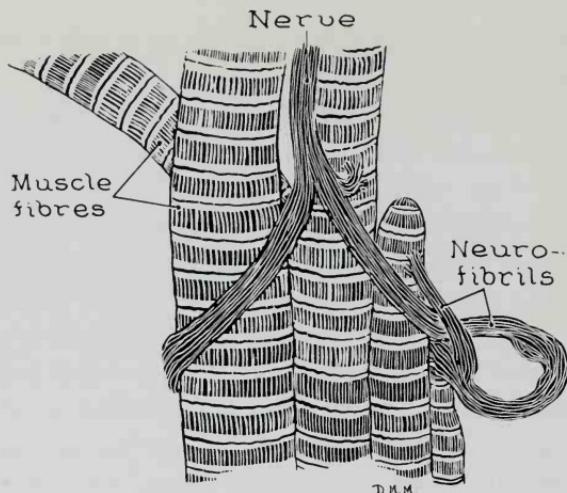
Fig. 8. Drawing of a photograph of nerve fibres ending on muscle fibres. (Magnification: about 500×.) (From Dutta and Basmajian, 1960.)

latter figure, they have calculated the size of the motor units. The latter method is rather questionable because we know that the motor nerve of a muscle contains many sensory and sympathetic fibres as well as motor fibres (fig. 9). Nonetheless, it is a method that does produce reasonable approximations.

Tergast (1873) estimated that the motor units of the sheep extraocular muscles have 3 to 10 muscle fibres; Bors (1926) estimated 5 to 6 for human extraocular muscles. More particularly, Feinstein *et al.* (1955) reported 9 muscle fibres per motor unit in the human lateral rectus, 25 in platysma, 108 in the first lumbrical of the hand and 2000 in the medial head of gastrocnemius. Van Harreveld (1947) reported 100 to 125 muscle fibres per motor unit in the sartorius of the rabbit; Berlendis and De Caro (1955), 27 in the stapedius and 30 in the tensor tympani of the rabbit; Wersäll (1958), 10 in the human tensor tympani; and Rüedi (1959), 2 to 3 muscle fibres per motor unit in the human laryngeal muscles.

Now, it is apparent that even the larger bundles of muscle fibres are quite small and that a strong contraction of a skeletal muscle must require the contraction of many such motor units. A fundamental principle governing such contraction is that there must
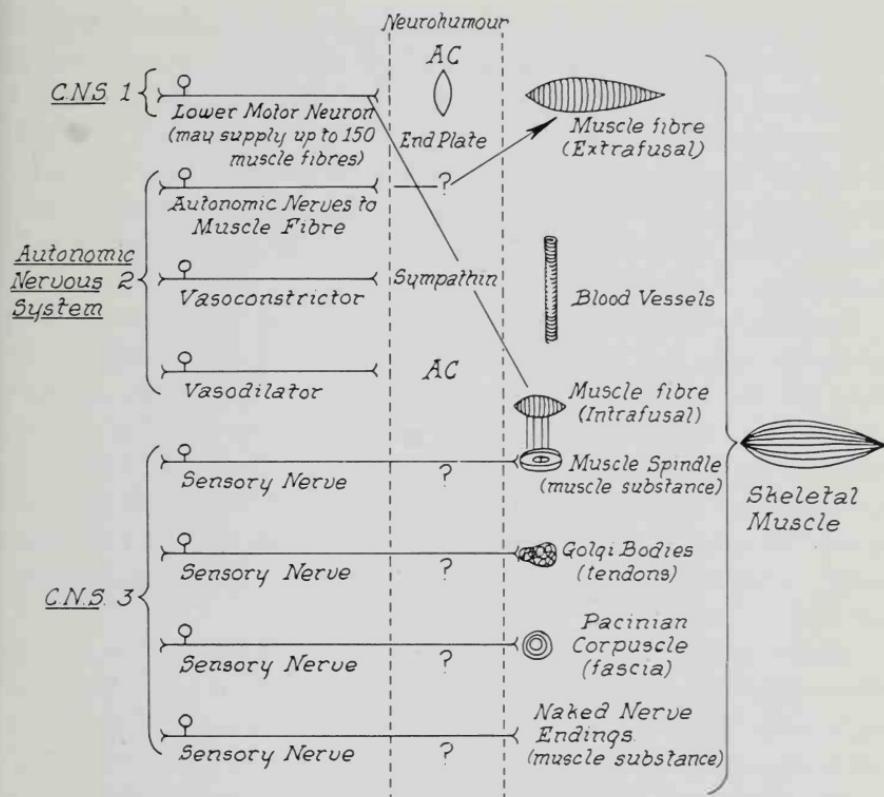
Fig. 9. Scheme of multiple innervation of skeletal muscle. (After Solandt, from Dutta and Basmajian, 1960.)

be a complete asynchrony of the motor unit contractions imposed by asynchronous volleys of impulses coming down the many axons. All the motor units are contracting and relaxing with twitch-like action at differing rates of up to 50 per second. The result of a continuous shower of twitches with different frequencies within a muscle is a smooth pull. In certain disturbances, however, the contractions become synchronized, resulting in a visible tremor.

Van Harreveld (1946, 1947) working with the rabbit's sartorius concluded that the fibres in a motor unit may be scattered and intermingled with fibres of other units. Thus the individual muscle

bundles one sees in cross section in routine histological prepara-
tions of normal striated muscles do not necessarily correspond to
individual motor units as such. Having paid attention to this, I
am convinced from my own studies (so far unorganized) that this
is indeed true in man as well. Norris and Irwin (1961) recently
went farther with their conclusion (supported by excellent evi-
dence) that in rat muscle the fibres of a motor unit are widely
scattered.

Buchthal, Guld and Rosenfalck (1957), using an elegant 12-lead
multielectrode technique, finally demonstrated quite conclusively
that (in the human biceps brachii) the spike potentials of each
motor unit were localized to an approximately circular region,
with an average diameter of 5 mm to which the fibres of the unit
are confined. (However the potentials could be traced in their
spread to over 20 mm distance.) That the area of 5 mm includes
many overlapping motor units has been equally convincingly
proved by Buchthal *et al*.

Motor endplates are located near the middles of the muscle
fibres (fig. 10). This has been shown by Coërs and Woolf (1959)
in human skeletal muscle, by Gurkow and Bast (1958) in the
trapezius and sternomastoid of the hamster, by Jarcho *et al.* (1952)
in the gracilis of the rat and by Dutta and myself (1960) in the
pharyngeal constrictors of the rabbit.

A question that arises occasionally concerns the actual amount
of physical work produced by a single motor unit. I have observed
on several occasions patients in whose various hand muscles all
the motor units but one are paralyzed. In such cases, repetitive
firing of the one unit is capable—but only rarely—of producing
a slight visible movement of the joint spanned. Others, including
Philippe Bauwens, have told me of similar experiences.

MOTOR UNIT POTENTIAL. When an impulse reaches the myo-
neural junction or motor endplate where the axonal branch
terminates on a muscle fibre, a wave of contraction spreads over
the fibre resulting in a brief twitch followed by rapid and complete
relaxation. The duration of this twitch is about 1 to 2 msec and
even up to 4 msec. During the brief twitch a minute electrical

Fig. 10. Bundle of parallel muscle fibres with endplates (dark dots) stained by cholinesterase technique. (From Coërs and Woolf, 1959.)

potential is generated which is dissipated into the surrounding tissues. Since all the muscle fibres of a motor unit do not contract at exactly the same time—some being delayed for several milliseconds—the electrical potential developed by the single twitch of all the fibres in the motor unit is prolonged to about 5 to 12 msec. (One millisecond is a thousandth of a second.) The electrical result of the motor unit twitch then is an electrical discharge with a median duration of 9 msec and a total amplitude measured in microvolts (μv) (or millionths of a volt). The majority of these

motor unit potentials is around 500 μv or 0.5 millivolts (mv) (fig.
11). When displayed on a cathode-ray oscilloscope or other display
device the result is a sharp spike that is most often biphasic, but
it may also have a more complex form. Generally, the larger the
motor unit potential registered, the larger is the motor unit pro-
ducing it. However, complicating factors, such as distance of the
unit from the electrodes, the types of electrodes and equipment
used, etc., enter into the final size of individual motor units re-
corded by the investigator. For further details, the reader should
consult the papers of Håkansson (1956, 1957a,b) and Buch-
thal (1959).

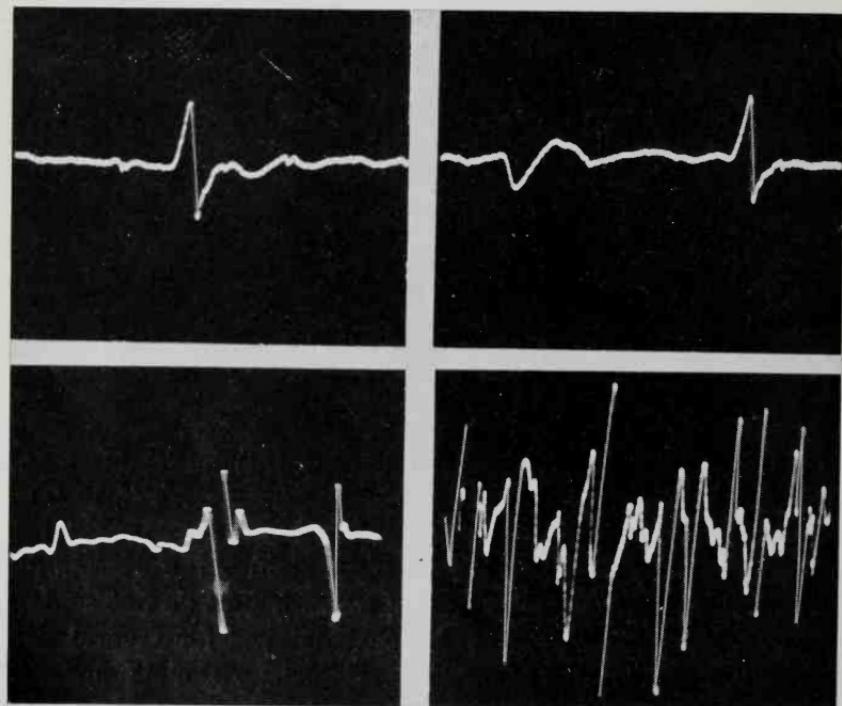Even in the same muscle, motor unit potentials in different

FIG. 11. Sample normal electromyograms showing one, two and
many superimposed motor unit potentials ("interference pattern"). The
single potential in the upper left corner had a measured amplitude of
0.8 mv and duration of 7 msec.

areas have significant differences in duration. For example, Kaiser and Petersén (1963, 1965) find that the durations (with a median of about 9 msec) are shorter in the long head than in the short head of biceps brachii. They also reported that average durations are about 0.3 msec longer for men than for women.

Petersén and Kugelberg (1949 *et seq.*) of Stockholm and Bauwens (1948 *et seq.*) of St. Thomas's Hospital in London have given the best descriptions of the characteristics of motor unit potentials. The former authors showed that the electrode type affects the recorded duration and amplitude of the action potentials. They demonstrated characteristic variations, e.g., the smallness of potentials in facial muscles as compared with those in muscles of the extremity.

MOTOR UNIT FREQUENCIES. Since the 1920's, it generally has been accepted that the normal *upper limit* of activation of motor units in man is about 50 per sec. Adrian and Bronk (1928, 1929) found this to be the case and it was confirmed by Smith (1934) and Lindsley (1935). There is some evidence that higher rates occur in other mammals (e.g., our unpublished findings suggest a rate of over 100 as a maximum in the lower limb muscles in rabbits). Marg, Tamler and Jampolsky (1962) believe that in human extraocular muscles, single motor units can fire at frequencies as high as 270 per sec or even more. This needs further investigation for their finding may be due to irritation of motor units by a probing needle.

As we shall see in Chapter 5, man can consciously control the rate of firing of individual units. Moreover, in recruitment (see below), the rate of firing of motor units is increased with stronger contractions.

MOTOR UNIT RECRUITMENT. It is now common knowledge that under normal conditions, the smaller potentials appear first with a slight contraction and as the force is increased larger and larger potentials are recruited, and all motor units increase their frequency of firing, as mentioned above. This is called the normal pattern of recruitment. It is absent in cases of partial lower motor neuron paralysis or, to be more specific, the small potentials never

appear, apparently because only the larger motor units have
survived.

Using microelectrodes, Norris and Gasteiger (1955) showed that
action potentials tended to increase in amplitude with excitation
and tension during isometric contractions of normal muscles.
They also elaborated on the concept of normal recruitment of
motor units. Hodes, Gribetz, Moskowitz and Wagman (1965)
found that the stimulation thresholds for human motor fibres in
the same nerve were lower for those of small diameter than for
those of large diameter. The smaller fibres supply the smaller
motor units which appear to be the most easily recruited in normal
voluntary contraction. In spite of this, we have found that man
can be trained to suppress the small, low-threshold units (Bas-
majian, 1963; Basmajian, Baeza and Fabrigar, 1965). This last
matter is discussed further in Chapter 5.

Muscle Fibre Potentials

Generally, it is agreed that a motor unit potential represents
the fusion of all accessible individual fibre potentials within a set
limit of time (Fleck, 1962). Therefore, studies of single fibre po-
tentials give promise of clarifying the mechanisms of contraction.
Buchthal and Engbaek (1963) determined the refractory period
and conduction velocity of the transmembrane potentials in single
frog muscle fibres at various temperatures. At 25°C the absolute
refractory period is 2 msec and the conduction velocity 2.8 metres
per second. Applying the voltage-clamp techniques for studying
isolated giant axons to single, surface fibres of frog muscles, Jen-
erick (1964) has been investigating the ionic currents associated
with the propagated impulse. He also is studying the relation-
ship between membrane voltage and membrane ionic current as
these are reflected in the phase plane trajectory of the response.
As yet no conclusive results have come from this promising ap-
proach.

Håkansson (1957b) recorded action potentials and the me-
chanical response of single muscle fibres, finding that the rising
phase of the intracellular action potential had traversed the whole

length of a fibre before the first sign of twitch tension appeared. Conduction velocities increase up to as much as 50% when the fibre is stretched—perhaps because of an increase of capacitance of the fibre membrane—while the twitch tension falls sharply.

Ekstedt (1964) has recorded single fibre potentials with special techniques *in vivo*. They are smooth biphasic spikes, often followed by terminal phases of low amplitude and long duration. His median value for voltage was 5.6 mV (with maximum of 25.2 mV). The median spike duration was 470 microseconds. He also demonstrated intermingling of fibres belonging to different motor units.

Fast and Slow Fibres

Electromyography in mammals offers only limited evidence for two types of contraction among the muscle fibres, one twitch-like and the other much slower. Indeed the weight of evidence in man indicates that such differences are insignificant. However, in invertebrates there is no question that two types of fibres exist and are important. Dorai Raj (1964) showed that in one muscle of the crab (the distal head of the accessory flexor) the muscle fibres of both types are innervated by the same single axon. In those vertebrates in which two types of muscle fibres have been found (e.g., the frog) there are separate axons for fast and slow fibres (Kuffler and Vaughan Williams, 1953). This also seems to be the case in those mammals (e.g., the cat) in which two types of fibres are proved to exist morphologically (Buller, Eccles and Eccles, 1960).

Whether a muscle is of the "slow" or "fast" type may depend to a large degree on its innervation. Slow soleus in rabbits shows continuous electromyographic activity while fast tibialis anterior is active only when brought into reflex action. If continuous moto-neuronal activity in soleus is abolished either by cutting its tendon of Achilles or by tenotomy combined with section of the spinal cord, then soleus becomes a fast muscle (Vrbová, 1963).

Effects of Age on EMG

Petersén and Kugelberg (1949) first reported a slight prolongation of the motor unit potential with advancing age. Later, Sacco,

Buchthal and Rosenfalck (1962) proved, in a systematic study
of abductor digiti quinti, biceps brachii and tibialis anterior of
normal infants (3 months of age) and adults, that the duration
of the action potentials was significantly shorter in the muscles of
the infants (fig. 12). This they explained in terms of the increase
in width of the endplate zone with growth. In persons of from 20
to 70 years of age, the mean duration of the action potentials in-
creased a further 25% in the brachial biceps, but they remained
unaltered in the abductor digiti quinti. Whenever the duration
of the action potentials increased with age, there was an increase
in mean amplitude. The increase in duration at advanced age was
attributed to an increased fibre density within the motor units
caused by a decrease in the volume of the muscle.

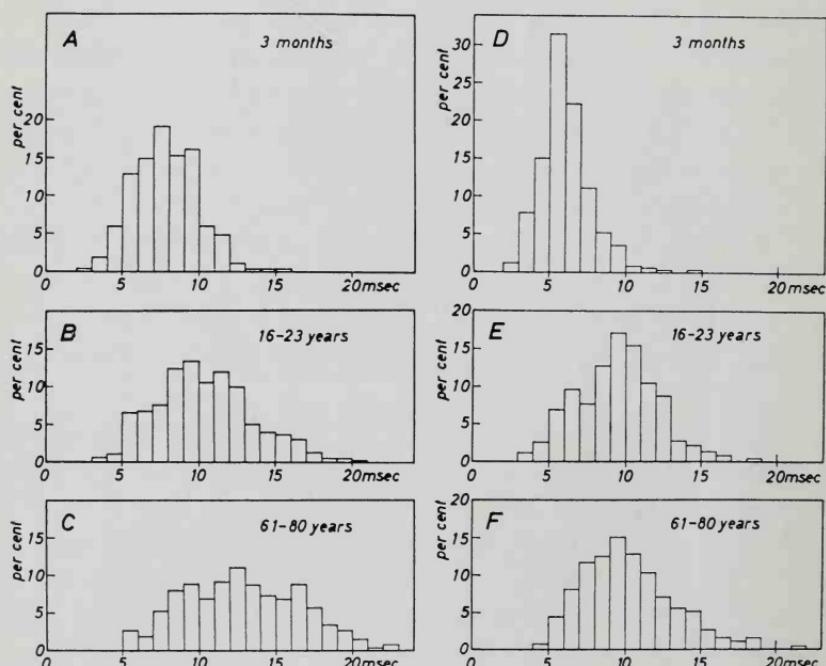With random insertion of concentric needle electrodes, the in-

Fig. 12. Histograms of duration of motor unit potentials recorded
with concentric electrodes from biceps brachii (A–C) and abductor digiti
quinti (D–F) of subjects of different ages. (From Sacco et al., 1962.)

cidence of potentials with an initial negative deflection was two
to three times greater in the abductor digiti quinti than in the
biceps brachii. This difference was most pronounced in infants
and indicated a relatively greater extent of the endplate zone in
the abductor digiti quinti than in the biceps.

In aged persons, the Russian physiologists Fudel-Osipova and
Grishko (1962) noted low voltage potentials (200 to 400 micro-
volts), a gradual (rather than an immediate) increase in amplitude
on sustained muscular contraction; they also found considerable
numbers of polyphasic, prolonged potentials of over 10 milli-
seconds' duration. Carlson, Alston and Feldman (1964) reported
consistent deviations from normal electromyographic findings
in aging skeletal muscle. On maximal contraction, they found an
obvious decrease in amplitude in the elderly age group when com-
pared with those of the younger normal controls (fig. 13). This
was interpreted on the basis of a decrease in the number of muscle
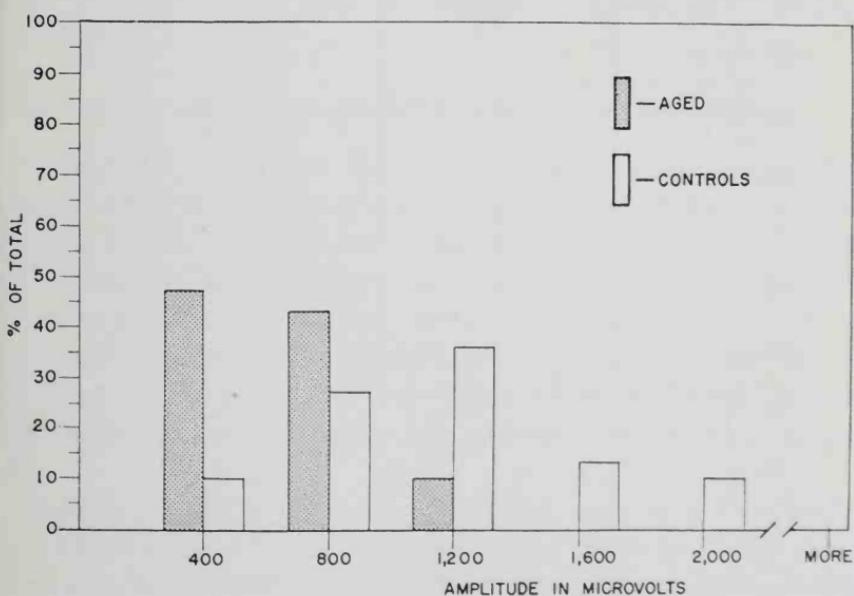fibres comprising the motor unit, a decrease in size of the indi-

FIG. 13. Comparison of emg amplitudes of aged individuals and
controls. (From Carlson *et al.*, 1964.)

vidual muscle fibres within the motor unit, or both. Perhaps, as Carlson and his colleagues suggest, with advanced age there is an inability of at least a portion of the fibres to maintain a sustained contraction.

They also found a considerable number of highly complex and long duration motor unit potentials in more than half of the older age group (fig. 14), suggesting that such a deviation from normal motor unit activity is a characteristic of aged skeletal muscle. (No polyphasic or long-duration potentials were noted in the young normal individuals who made up their control group.)

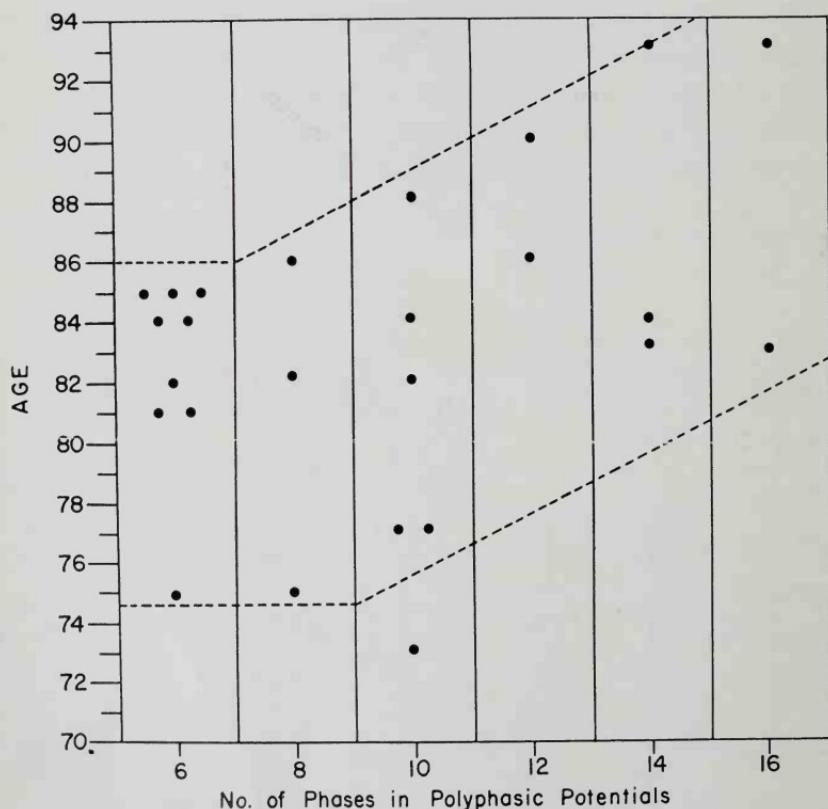In view of the absence of denervation (fibrillation) potentials

FIG. 14. Complexity of EMG as a function of age (increase in polyphasic potentials). (From Carlson et al., 1964.)

in all aged subjects and the finding of normal motor nerve conduction velocities, Carlson *et al.* could not relate the presence of complex potentials to a neurogenic disturbance. A delay in transmission at the endplate of a number of motor unit fibres could account for such asynchronous motor unit behaviour. Similarly, they thought that this could be explained on the basis of physiological alteration of the muscle fibre with an associated delay in fibre response.

Mitolo's (1964) limited investigation dealt with the decrease of muscular "tonus" and the training capacity for physical exercise in old age, providing only general conclusions on the benefits of careful exercises.

That changes in the electromyogram occur with advancing years is now undeniable in man. These also occur in other species as illustrated by work of Holliday, Van Meter, Julian and Asmundson (1965): hyperexcitability to mechanical stimuli (movement of the needle electrode) is the rule in chicks, but it diminishes with increasing age until it disappears completely in adult chickens.

The Place of Electromyography in Biology and Medicine

A brief review of the special role that electromyography has assumed in scientific research is a proper ending for this introductory chapter. As with other scientific techniques, this one arose in response to a need. Obviously, the actions and functions of muscle had not been fully understood in spite of continued interest and investigation. Notwithstanding the admirable zeal of many investigators, serious limitations in the classical methods of muscle-evaluation account for the gaps and errors in our knowledge.

The classical methods of study on which most of our knowledge of muscle function have been based are: (1) topographical study of dead muscles combined with mechanistic calculations of what they "ought to do," (2) direct electrical stimulation, (3) visual observation and palpation through the skin of the muscles in ac-

tion and (4) study of paralyzed patients and an evaluation of the deficits.

Except in some obvious applications, the above methods are incomplete, whether they are taken alone or all together. They cannot adequately reveal—as electromyography can—the function of deep, impalpable muscles and the exact time-sequences of activity. It is not enough to estimate by classical methods what a muscle *can do* or *might do*. Electromyography is unique in revealing what a muscle actually *does* at any moment during various movements and postures. Moreover, it reveals objectively the fine interplay or coordination of muscles; this is patently impossible by any other means.

Apparatus and Technique

THE electrodes used in electromyography could well be—and actually are—of a wide variety of types and construction. Their use depends on the first principle that they must be relatively harmless and must be brought close enough to the muscle under study to pick up its electrical changes.

The two main types of electrodes used for the study of muscle dynamics are surface (or "skin") electrodes and inserted (wire and needle) electrodes. Each has its advantages and its limitations, and they will now be described.

Surface Electrodes

Most often one finds that the simple silver discs used widely in electroencephalography are adapted for electromyography (fig. 15). Their advantages revolve around one point: convenience. For example, they are readily obtained from supply houses; they can be applied to the skin after very little training and with reasonable success (within the limitations to be discussed); and they give little discomfort to the subject.

Extremely important in the technique of applying surface electrodes is the ensuring that the electrical insulation between muscle
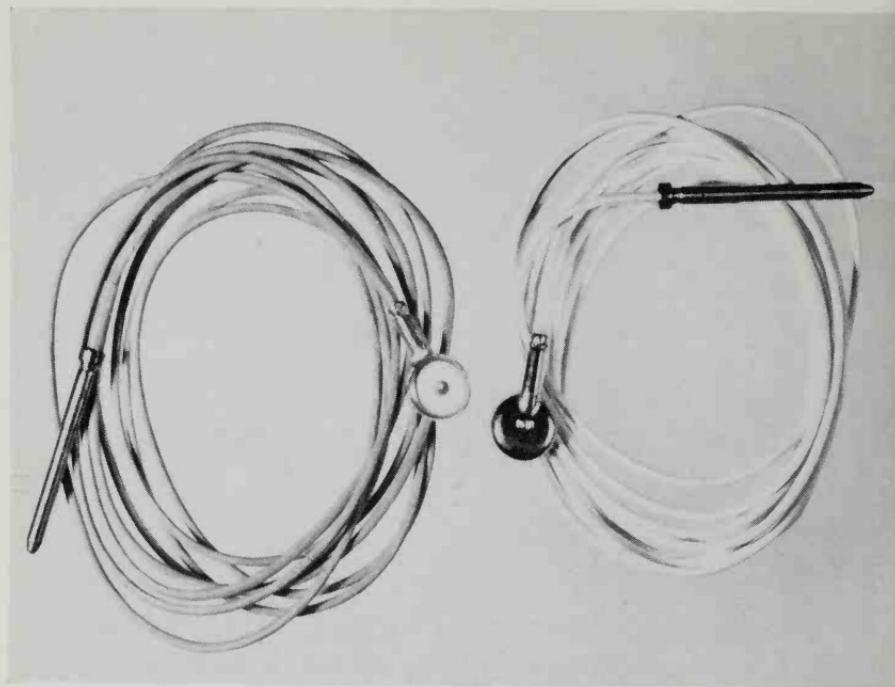
FIG. 15. Silver-disc surface electrodes (electroencephalographic type)

and electrode is reduced to a minimum. Obviously, since a poor contact must be avoided, continued pressure is important. Fortunately, the pressure provided by the adhesive strips used for the securing of the electrodes is usually adequate. Electrical contact is greatly improved by the use of a saline "electrode jelly;" this is retained between electrode and skin by making the silver disc slightly concave on the aspect to be applied to the skin. The dead surface layer of the skin along with its protective oils must be removed to lower the electrical resistance to practical levels (of around 3000 ohms). This is best done by light abrasion of the skin at the site chosen for electrode application. In recent years we have found that it is best produced by "rubbing in" those types of electrode jelly that have powdered abrasive included in their formula.

Modified types of surface electrodes may be used. For example,

Bauwens and his colleagues at St. Thomas's Hospital, London, use small plastic suction cups incorporating two electrodes; the air is evacuated from the cup after it has been applied with jelly to the skin. Another type of suction cup electrode that is available commercially is made of rubber and can be applied with moderate ease; they are obtainable from Phillips and Bronson, Ltd., 8 Millfields Rd., London (fig. 16). Harris, Rosov, Cooper and Lysaught (1964) recommend a system that provides suction to multiple, metallic-cup electrodes through a manifold. According to these authors, the electrodes successfully grip the surface of skin or mucosa with a minimum of preparation. An excellent, inexpensive suction cup electrode of very simple design has been described by Moore (1966).

Surface electrodes may be used in pairs for localizing the pick-up or they may be used with a more distant common ground or earthing electrode. In either case, the chief disadvantages of surface electrodes are that they can be used only with superficial muscles and that their pick-up is generally too widespread. Thus, many of the results obtained could be deduced with reasonable care from palpation and direct inspection of the muscles in action. Perhaps the chief usefulness of surface electrodes appears where the simultaneous activity or interplay of activity is being studied
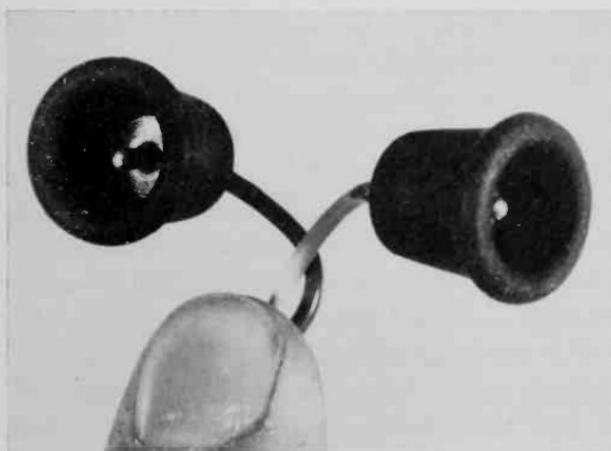

FIG. 16. Rubber suction-cup electrodes (Phillips-Bronson type)

in a fairly large group of muscles under conditions where palpation is almost impossible (e.g., in the muscles of the lower limb during walking).

O'Connell and Gardner (1963) give an excellent review of the special problems of technique when using surface electrodes for kinesiological studies; and Grossman and Weiner (1966) caution psychologists against facile acceptance of integrated surface electromyography, because there are many technical errors that creep in. If their warnings are heeded, substantial progress can be made with skin electrodes in uncomplicated, general investigations. Yet, as indicated above, one should not reduce the effectiveness of research because of imagined limitations. Inserted electrodes are no longer the imposing instruments they once were and are to be preferred for most kinesiology. The fine-wire electrodes described on p. 32 are easy to insert and they are as easy to tolerate as skin electrodes are.

We must condemn the exclusive use of surface electrodes to study fine movements, deep muscles, the presence or absence of activity in various postures and, in short, in any circumstances where precision is desirable.

Inserted Electrodes

NEEDLE ELECTRODES. By far the commonest inserted electrode is the needle electrode, but occasionally other types are also used to advantage. The commonest needle electrode, in turn, is the bipolar concentric-needle electrode first described by Adrian and Bronk (1929) and used widely by clinical electromyographers and to a lesser extent by anatomists (Basmajian, 1958a; Becker and Chamberlin, 1960). The concentric needle electrode consists of a simple stainless steel hypodermic needle which contains an insulated wire in its barrel (fig. 17). The tip of the wire is bared and acts as one electrode while the barrel of the needle acts as the other. The outer needle may be insulated (except for its tip). A second wire can be included and used as the second electrode; in this case the barrel of the needle is used as an insulator or "iso-
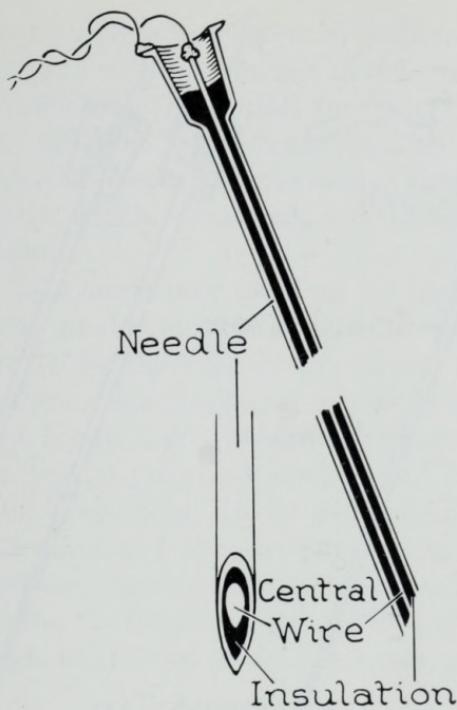
Fig. 17. Concentric needle electrode

lator." This last type of electrode is extremely localizing and so it is seldom used in kinesiology.

Many investigators use the unipolar type of electrode introduced by Jasper and his colleagues in Montreal and consisting basically of little more than a fine insulated sewing-needle (fig. 18) (Jasper and Ballem, 1949). Though it is excellent for clinical investigation (where I once used it frequently), the unipolar electrode usually proves rather clumsy for multiple simultaneous pick-ups because it requires to be paired with a neighbouring surface electrode or another unipolar needle.

Sterilization of needle electrodes may offer some problems. No difficulties have been encountered after many years' experience in the use of ethanol as a bath in which the entire electrode is emersed for several hours before use. Equally effective are auto-
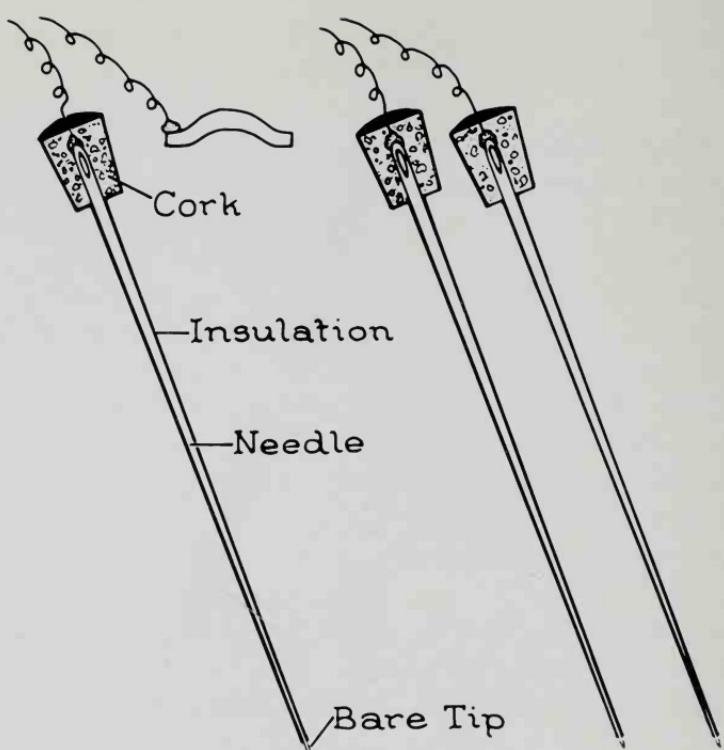
FIG. 18. Unipolar needle electrodes (modified Jasper type). *Left,* paired with silver-disc skin electrode; *right,* paired.

claving and dry heat. In the latter case, there is available a convenient gadget which sterilizes needles at 470°F in a matter of moments. It is a small sterilizer that employs heated glass beads in which the needles are buried (EMG Associates, 217 Park Row, New York).

Lundervold and Choh-Luh Li (1953) of Oslo concluded after comparing different kinds of needle electrodes that the unipolar electrode is the best for studying fibre potentials and motor-unit potentials but the difference is not significant for kinesiological studies. Concentric needle electrodes were proved to be preferable in some applications. Independently, Landau (1951) arrived at essentially the same conclusions.

Jarcho *et al.* (1952, 1958) demonstrated conclusively that po-

tentials from contractions produced by indirect stimulation *via* the motor nerve vary with the position of the recording electrodes. Admittedly, however, the potentials resulting from nerve-stimulation are quite different from those obtained during a normal voluntary contraction, being a summation of many units contracting simultaneously, which is decidedly not the case with volitional muscle contraction.

On occasion as a particular problem on hand demanded, we have used various pliable electrodes made of stainless steel wire. For example, to study the very deeply placed human sphincter urethrae, such a wire was implanted in that muscle (see p. 278). Insulated except for its tip, the wire was first loosely threaded through a long "spinal puncture needle" and its very end bent back into a hook. The spinal needle was used to direct the wire to its desired location and then withdrawn leaving the hook in proper place and the other end of the wire dangling and ready to be connected to the electromyograph. A firm tug sufficed to withdraw the electrode at the end of the experiments.

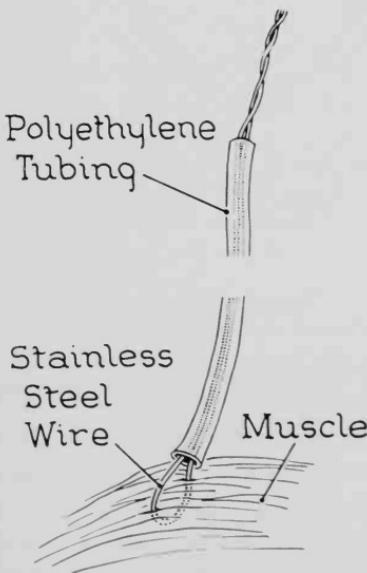Polyethylene
Tubing

Stainless
Steel
Wire

Muscle

FIG. 19. Insulated, stainless steel, wire electrode for pharyngeal muscles of rabbits. (From Basmajian and Dutta, 1961a.)

We have made other wire electrodes of a similar type but modified in detail for study of pharyngeal muscles in rabbits and in man (figs. 19, 20 and 21) . Similar electrodes have been also used by Long *et al.* (1960) for a study of intrinsic muscles
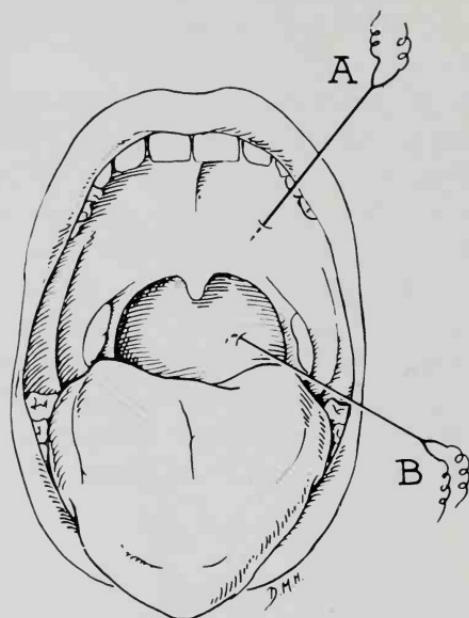

Fig. 20. Bipolar, insulated, wire electrodes for transmucosal palatal and pharyngeal electromyography in man. (From Basmajian and Dutta, 1961b.)
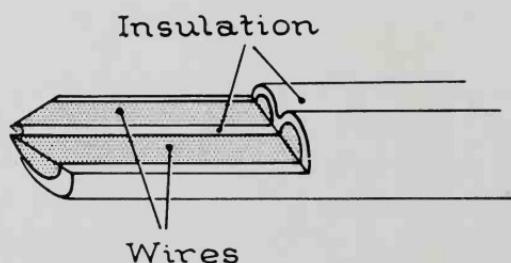

Fig. 21. Cut-away diagram of close-up of tip of electrodes in figure 20. (From Basmajian and Dutta, 1961b.)
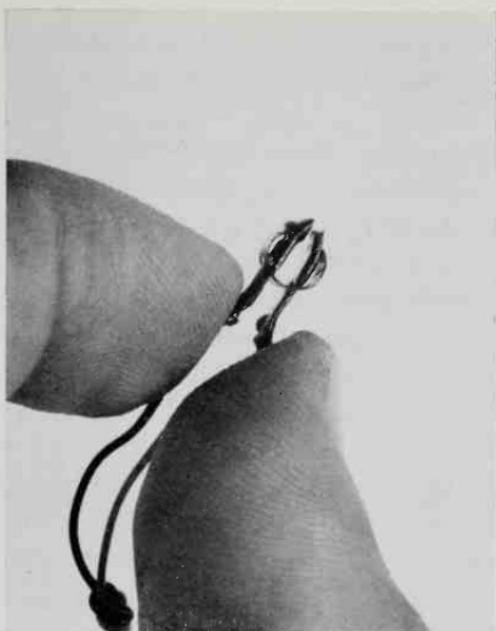
FIG. 22. Bipolar clip-on electrode for diaphragm. (Basmajian and Boyd.)

in the hand and by Close *et al.* (1960). Recently we have been using special tiny bipolar clip-on electrodes for the diaphragm (fig. 22) (Boyd and Basmajian, 1963). Schoolman and Fink (1963) have also devised electrodes which may be chronically fastened to the diaphragm of experimental animals. Surely there is no limitation to the possible electrodes one might invent for special applications.

In experiments where chronic intramuscular electrodes are required, it is sometimes desirable to avoid wires emerging through the skin. Oganisyan and Ivanova (1964) of Moscow described a novel technique in making recordings from such chronically implanted electrodes in dogs. Subcutaneously they bury a rubber capsule containing an electroconductive gelatinous mass from which a wire electrode runs into the muscle. Whenever recordings are desired, connection to amplifier input wires is completed by thrusting a needle through the skin into the capsule. I have had

the pleasure of seeing scientists at the Institute of Higher Nervous Activity and Neurophysiology employing this technique successfully.

FINE-WIRE ELECTRODES. Since 1961, for routine multi-electrode studies, my colleagues and I have almost abandoned both surface and needle electrodes in favour of our fine-wire, bipolar electrodes (Basmajian and Stecko, 1962). Similar electrodes that differ only in the details of their construction have been independently developed by a number of other research centres, notably Highland View Hospital in Cleveland. Fine-wire electrodes have proved a boon to kinesiological studies because they are: (1) extremely fine (and therefore painless), (2) easily implanted and withdrawn, (3) as broad in their pick-up from a specific muscle as are the best surface electrodes, and yet, (4) they give beautiful, sharp spikes similar to those from needle electrodes. At the present time this type of electrode approaches the ideal for detailed kinesiology. As Sutton (1962) has shown, inserted electrodes with 1 mm of exposed tip record the voltages from a muscle much better than surface electrodes. But in clinical types of studies and in studies where the electrode must be moved about in an exploratory fashion, needle electrodes remain the obvious choice.

In most serious scientific work, fine-wire electrodes are casting a progressively deeper pall on surface electrodes which will of course be useful in crude or generalized studies or studies in which the output of a whole large area or group of muscles is desired. Such applications do exist, but, for accurate indication of activity in single muscles, the fine-wire electrode is preferred because it gives as great an output as surface electrodes along with an incomparable isolation of pick-up to an individual whole muscle.

Our bipolar fine-wire electrodes are made from a nylon-insulated, Karma alloy wire, 25 microns in diameter (manufactured by Driver Harris Corp., Harrison, New Jersey). The steps for making an electrode (fig. 23) are as follows: (1) A double strand of the nylon-coated wire is passed through the shaft of a hypodermic needle. A small loop is left distally, and 5 to 7 cm of wire

A strand of Nylon
Karma Alloy wire looped
through a 27 gauge Hypodermic
needle

Nylon insulation
burned off Distally
and Proximally

Distal ends staggered

Staggered distal
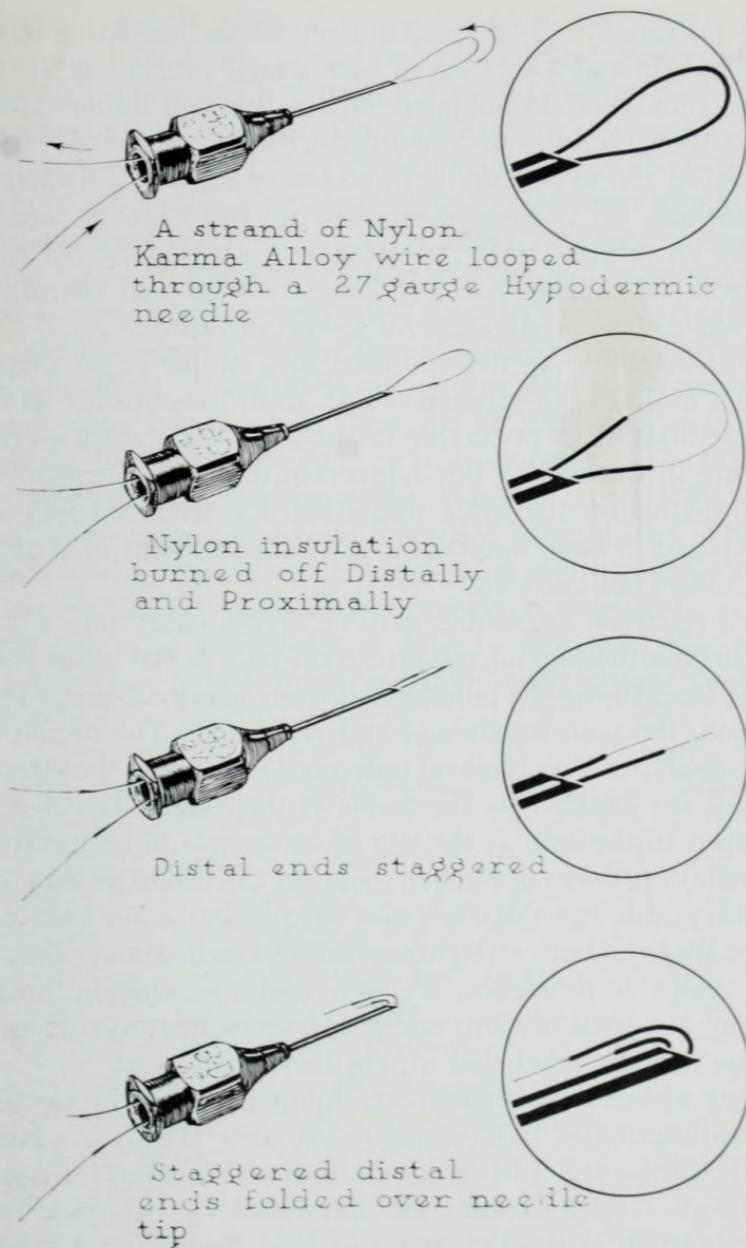ends folded over needle
tip

FIG. 23. Steps in making a bipolar fine-wire electrode with its carrier needle used for insertion (Basmajian and Stecko, 1962).

is left proximally. (2) A small amount of the insulating nylon at the distal tip and 3 to 4 cm of each strand proximally are burnt off in a Bunsen or alcohol-lamp flame—although Robert McLeod, now at the University of New Brunswick, Canada, finds chemical removal of the nylon results in a cleaner surface (personal communication). (3) The loop is cut, leaving 1 to 2 mm of bared wire distally on each strand. These bare ends are staggered so that they will not come in contact. They are then bent sharply back to lie against the needle shaft for a short distance.

The assemblies are dry-sterilized in a simple paper folder for 60 min. at 130°C (or autoclaved at 15 lb pressure for 30 min.). Dry sterilization is preferable because it avoids condensation of moisture in the needle, but temperatures must be controlled to avoid melting off the nylon insulation. Electrode assemblies can be prepared in large numbers in advance and kept in their sterilized folders until needed.

Such electrode assemblies may be driven easily into a muscle without anesthesia, and the attendant pain is the usual pain resulting from the needle puncture. If fresh, sharp, 27-gauge needles are used, the pain is minimal and transitory. The needle withdraws easily, and its removal only rarely dislodges the electrodes for they are retained by the hooks at their ends. The electrodes are taped to the skin at the site of emergence to ensure that an accidental tug does not remove them. At the end of an experiment a gentle pull brings the electrodes out painlessly, for each wire is so fine that the barb straightens out on traction and offers little if any palpable resistance. We have had no accidental breakage in many hundreds of uses; nor would we be disturbed if we had, because the fine nylon-clad wire is innocuous.

If one wishes to insert individual unipolar fine-wire electrodes, the modification of our technique by Scott (1965) is admirable and avoids the use of barbs to retain the wires when the needle is withdrawn. The technique was developed by Professor Scott's research group at the University of New Brunswick, Canada. It depends upon the use of the hypodermic needle not only to insert the electrode but also to act as a cutting instrument once the

electrode is deep in place. A single strand of fine wire is passed through the hypodermic needle and a long loop turned back from the needle tip (fig. 24). The unit is sterilized and inserted into the muscle in the usual manner. The wire is cut by pulling on its free ends, one of which emerges from the skin alongside the needle and one out of the needle. Both needle and its contained wire are then withdrawn leaving one unbarbed wire deep in place.

After a period of use, we found only one tedious step or complication with fine-wire electrodes, *viz.*, the connection of the almost invisible filament to the larger, braided, lead-in wire of the EMG amplifiers. Others have met and overcome this problem in different ways. For example, Long and his colleagues at Highland View Hospital in Cleveland rely on pre-connection of the fine-wires to standard wires to produce a unit. However, when their needles are withdrawn, they cannot be discarded because they cannot be drawn over the connections. Because we prefer disposable needles and electrodes that are used only once and discarded, we make connections after the needle is entirely removed. Making the connections can be a tedious procedure when it must be done a
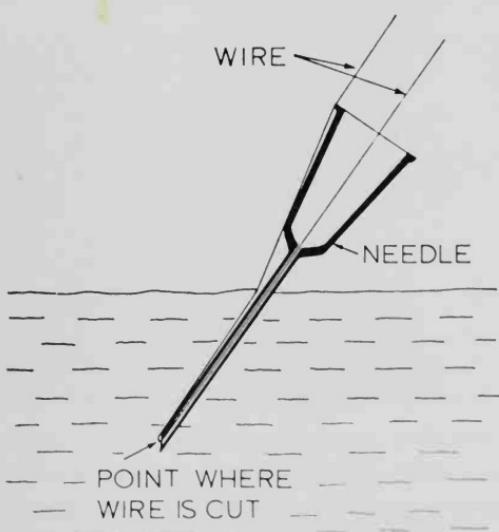

WIRE

NEEDLE

POINT WHERE
WIRE IS CUT

Fig. 24. Unipolar fine-wire electrode. (From Scott, 1965)

dozen times for one experimental set-up. Therefore, being lazy,
we developed a simple method.

After finding that soldering, microwelding and miniature alli-
gator clamps all have drawbacks, we devised a spring-wire coil
connector (Basmajian, Forrest and Shine, 1966) which has proved
itself in two years of extended usage. It is a brass spring (about
4 mm in diameter by 12 mm in length) soldered permanently to
the free ends of each amplifier lead-in wire. The spring is tightly
wound from a resilient 22 "spring-brass" wire which gives consid-
erable pinch between adjacent coils. This type of hard brass wire
is available through ordinary commercial channels.

To make connection to the fine-wire electrodes after they have
been inserted and the needle discarded, the spring is bent slightly
between the thumb and index finger. This spreads the coils and
allows the bared end of the electrode wire to be slipped between
one or two pairs of coils (fig. 25). Released, the spring clamps the
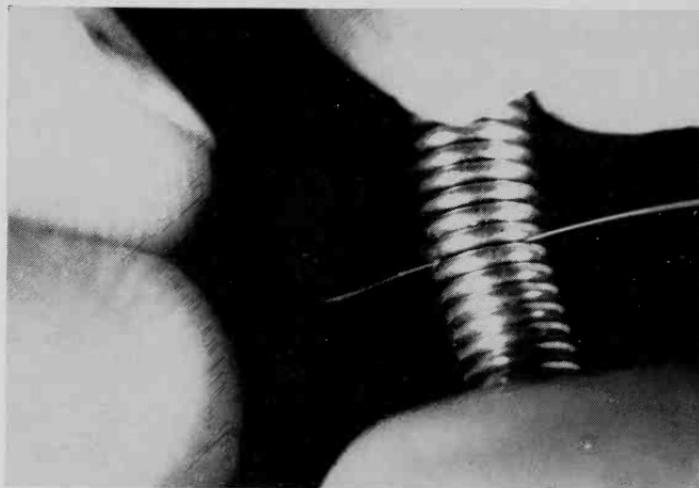fine wire and gives good electrical connection instantly. Wrapping

Fig. 25. Special spring-connector for fine-wire electrodes (Basmajian,
Forrest and Shine, 1966). Here a coarser electrode-wire is used for visi-
bility; it is slipped between two adjacent opened turns of the coil which
will clamp down on it when the pressure of the fingers is removed from
the ends of the coil.

a bit of adhesive tape around the connection (for protection and insulation) completes a procedure that takes only moments and saves many tedious minutes required by other methods.

Another ingenious approach to the problem of connecting fine wires to coarser wires for the purpose of kinesiological experiments has been devised by Rinker (personal communication, 1966). He makes the connection with the quick drying paint or ink that he found being used in industry to repair broken connections in etched electronic circuits. (A minor disadvantage of his technique is the need for a small plaque against which the connections can be made.) Now that fine wire electrodes are gaining wide acceptance, no doubt other useful innovations are to be expected.

Apparatus

Electromyographs range from the most makeshift homemade equipment—some of which is first rate—to fine looking, massively impressive, beautifully engineered, custom-made (and expensive) "machines"—some of which are actually as good as they look. Many kinesiologists are confined (or apparently choose to confine themselves) to using discarded EEG or ECG equipment; sometimes this apparatus is used for EMG's without proper adjustments having been made to record what is a completely different phenomenon. This practice can only tarnish electromyography. On the other hand, with proper adjustments modern EEG equipment can be adapted nicely to most routine non-clinical EMG recording.

Basically, an electromyograph is a high gain amplifier with a preference or selectivity for frequencies in the range from about 10 to several thousand cycles per second (cps). (Recently it has become conventional to use Hz—for Hertz—to denote cycles per second.) Keith J. Hayes (1960) suggests that the sharply peaked spectra of motor unit potentials derived with surface electrodes make the use of amplifiers with limited frequency response practical. He finds several advantages in rejecting frequencies below 20 cps and above 200 cps. Then, amplifier "noise," general non-muscular "tissue noise" (which he found to be even more disturb-

ing) and movement artifact would be largely eliminated without significant loss of motor unit potentials. He suggests an upper limit of 200 cps as satisfactory but admits that a somewhat higher frequency response might be desirable. I would agree that 1000 cps as the upper limit of the band width is excellent but would prefer the provision of high and low frequency cut-off switches, such as in my own apparatus, to be described below.

The ideal research apparatus is exemplified by the special six-channel EMG used in our laboratory and built by Stanley Cox, Ltd., London (Basmajian, 1958a). The Stanley Cox six-channel electromyograph (fig. 26) consists essentially of six identical, but entirely separate, amplifiers. Each amplifier is fitted with a small cathode-ray tube for monitoring (figs. 27 and 28). The smallness of the tube does not detract from the usefulness of the cathode-ray oscilloscope but provides much the cheapest way of getting the desired information. These amplifiers are situated together with a control unit on the top of a compact metal cabinet (fig. 27). Situated on the floor of the cabinet is the power-supply unit next to a light-proof compartment that contains six small cathode-ray tubes placed in a row along with a seventh time-marker tube. The traces on these tubes are recorded in seven parallel rows on 100-foot lengths of photographic film by a Cossar 35-mm linagraph camera affixed to the side of the cabinet (fig. 26). We have found that one roll of film is adequate for the recording of several afternoons' work. Although there is a constant sweep of the traces on the monitor tubes, the beam of the recording tubes has no x-axis deflection; this is provided by the continuous movements of the film through the camera while recording. The wave-form of the time marker is a series of spikes, the interval between each spike being 10 msec (fig. 29).

The camera has three speeds and is set in motion by a single switch. To prevent damage to the phosphor of the recording tubes the beams become bright only when the camera is switched on.

The amplifiers are adjustable for different conditions. For example, the frequency response may be modified to attenuate unwanted signals. Normally, recordings can be made with the fre-
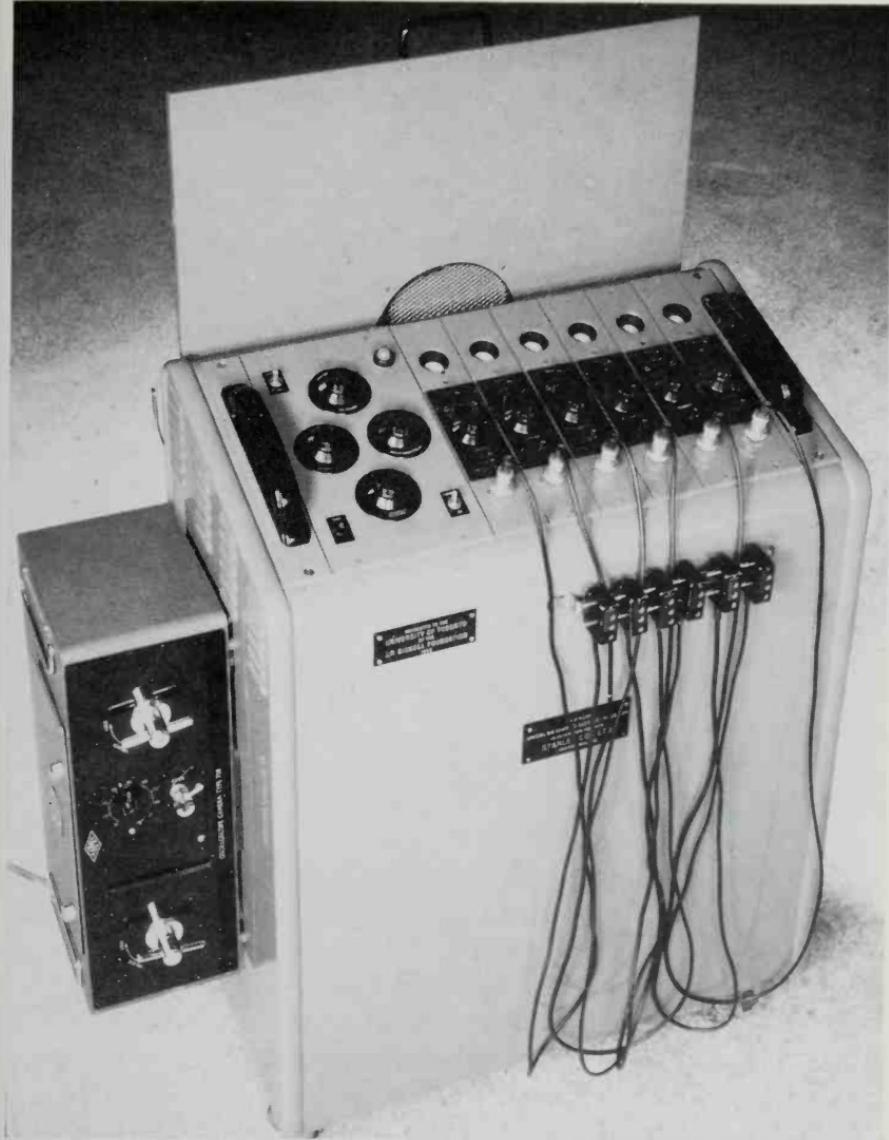
Fig. 26. Stanley Cox six-channel electromyograph. The row of six independent amplifiers (each with its separate controls and the face of a 1-inch monitor tube) is seen on the upper sloping surface. Rising from the back of the cabinet is a loudspeaker which can be switched from channel to channel for "sound monitoring" of the signals. The panel to the left of the amplifier provides the general controls and a jack for connecting a larger oscilloscope when required. The linograph camera attached to the left side "looks" through a porthole at the seven recording tubes located in the left lower part of the cabinet. (From Basmajian, 1958a.)
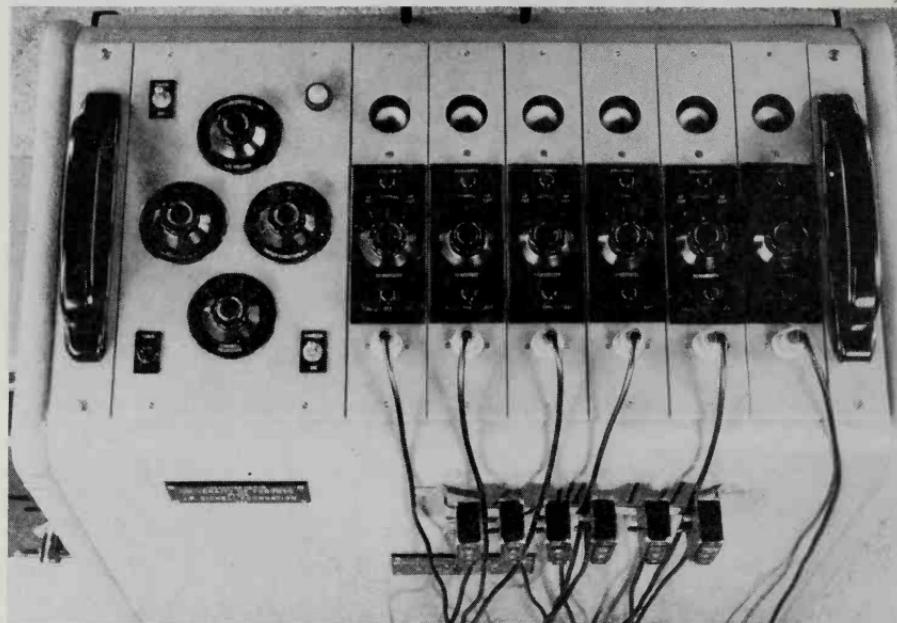
FIG. 27. Close-up of control panel of special electromyograph. Faces of six small cathode-ray oscilloscopes used for monitoring seen in a row across top. (From Basmajian, 1958a.)

quency response unmodified and is flat from 10 to 5000 cps which is the most useful for muscle potentials. Higher frequencies can be cut off at 1000 cps by the flick of a switch. The gain of the amplifier increases in 10-db steps, the maximum voltage gain being 10^6. (This means a deflection of 1 cm on the monitor tube for an input of 30 μv.) The rejection ratio of in-phase to out-of-phase signals is greater than 5000 to 1.

Several types of commercial electromyographs in wide use are produced for clinical work, but these may be adapted for anatomical studies; for example, the routine clinical electromyograph now produced in England by Stanley Cox, Ltd. Among the best known in the U.S.A. are those produced by the Medcraft Electric Corp., the Meditron Company and the Teca Corporation; and in Europe the DISA EMG appears to be widely used.

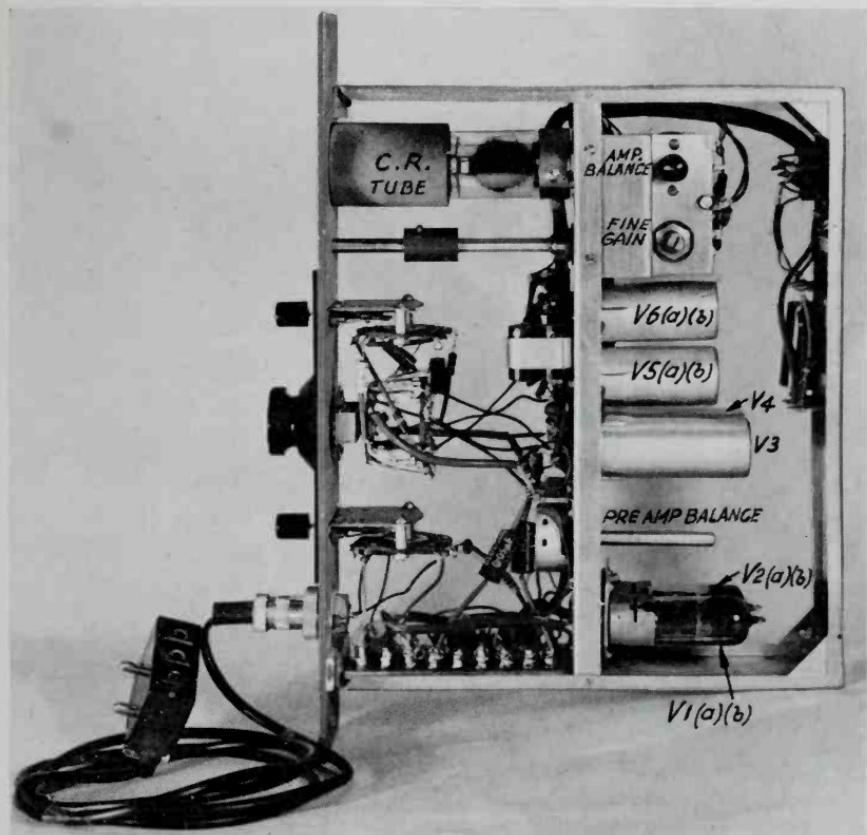To aid those who are embarking on electromyographic studies

FIG. 28. Side view of one of the amplifiers removed from cabinet of special electromyograph. (From Basmajian, 1958a.)

for the first time, an Appendix (p. 357) has been prepared to describe some of the available commercial EMG equipment.

Transistorized electromyographic amplifiers are coming into wider use, and transistors may someday replace most electronic tubes. One now can build an electromyograph so small that it may be combined with an FM transmitter and implanted within the body of experimental animals (fig. 30). Without any doubt, engineering and technology can and will reduce the size of such equipment even further while greatly improving general performance.
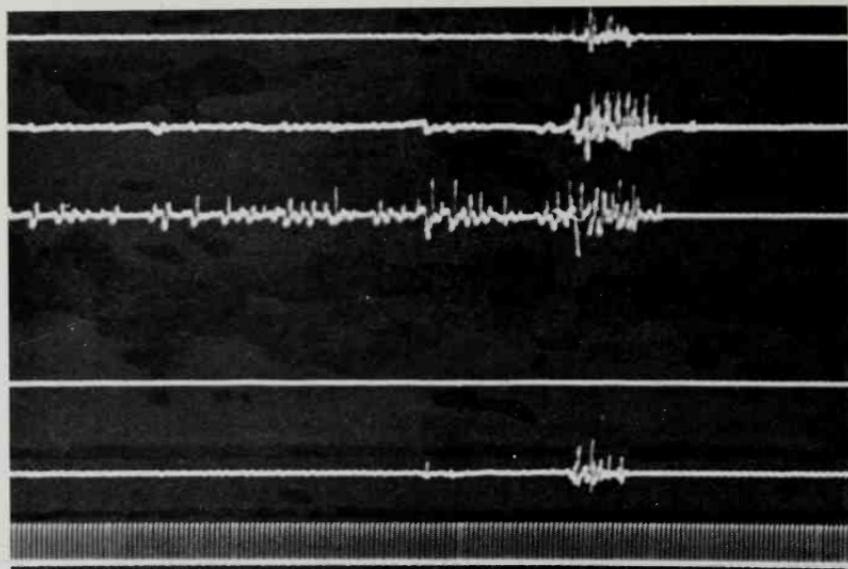
Fig. 29. A short segment of recording from five channels plus time marker (*bottom row*), made with special electromyograph. (From Basmajian, 1958a.)
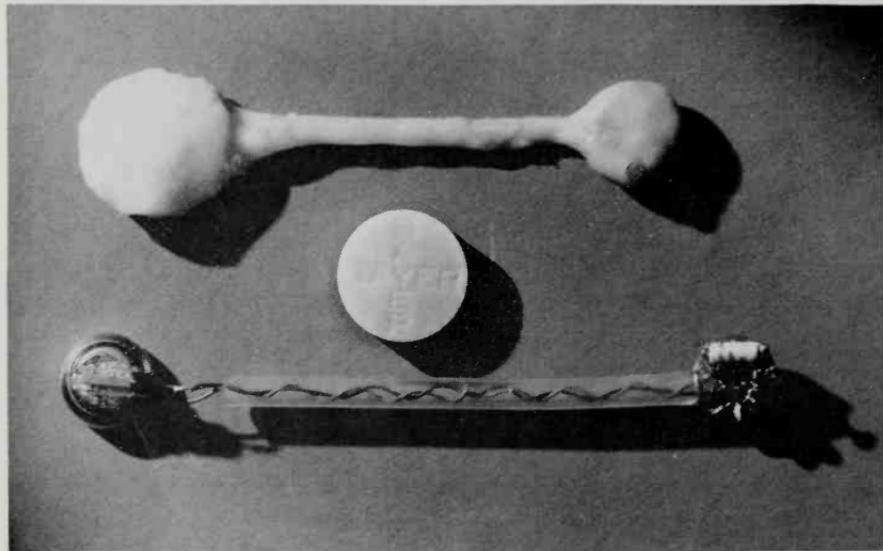

Fig. 30. The K-5 implantable miniature EMG plus FM radiotransmitter with and without its protective Silastic coating, developed at the Case Institute of Technology (compared with an aspirin tablet). The battery is the larger mass to the left. (Photograph through the courtesy of Dr. W. H. Ko.)

Multiwire Cables

In kinesiological studies where gross movements are under study, movement artifacts present a constant annoyance. These may arise from the movement of skin electrodes; but, more important, they arise from the movements of the wires and cables leading from the electrodes to the amplifiers. The greater the number of leads, the greater the difficulties. Various attacks have been made on the problem. Kamp, Kok and de Quartel (1965) built and described a multi-wire cable depending on the pliant shielding and protection of as many as 16 wires. We have had the good fortune of coming upon a new commercial multi-wire cable material (Super-flex Conductor manufactured by Cicoil Corp., Van Nuys, Calif.) This cable has proved to be particularly useful and free from trouble. It consists of many parallel wires embedded in a thin ribbon of soft plastic (fig. 31).
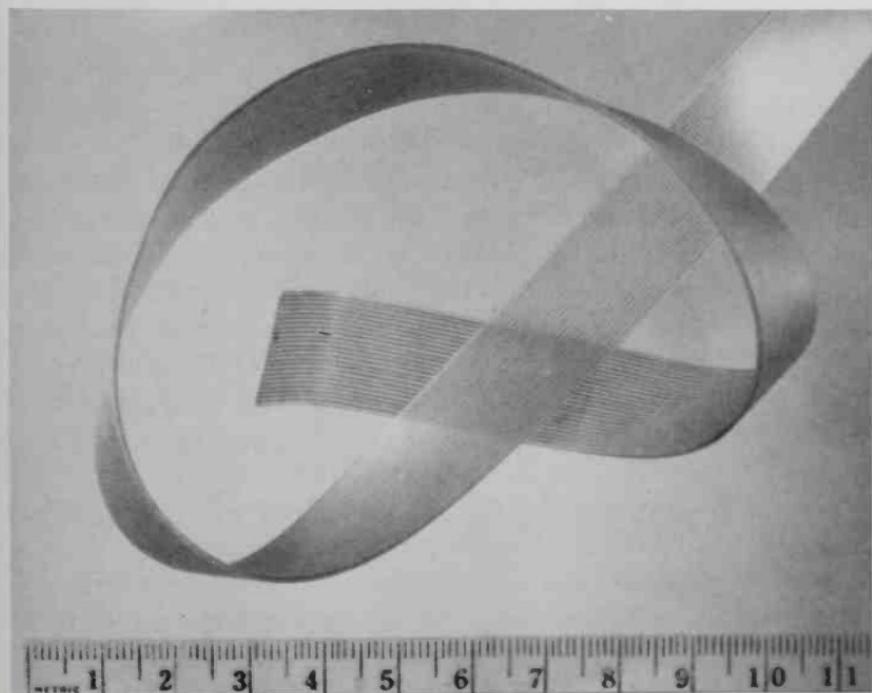

Fig. 31. Super-flex multiwire cable. Twenty-four fine wires are embedded in a pliable ribbon of plastic.

Telemetering of EMG

As with any electric signals, EMG potentials can be transmitted for long distances either by telephone lines (Levine, *et al.*, 1964) or by FM radio. The latter is particularly useful in field studies of wild animals or in experiments in which the subjects should be completely unfettered by dragging cables (as in running, jumping, etc.). A number of excellent telemetering systems have been described and good standard equipment is available from commercial sources. Our laboratory has had limited experience with multi-channel telemetering until recently when we started more extensive trials. Single-channel telemetering of EMG is much simpler for obvious reasons and many groups including ours have accumulated convincing evidence of its value. One might expect that within a few years extensive use of multi-channel EMG telemetry will be quite common.

Recorders and Their Evaluation

Recordings of motor unit potentials are made by many devices with varying success. Most convenient for the beginner and least wasteful is the pen-writing recorder such as one finds usually on EEG equipment (fig. 32). Writing on a moving strip of paper with as many as 24 independent channels simultaneously, this type of recorder is cheap and is easily serviced. However, it has one serious drawback when one is attempting to do accurate work in that the inherent responsiveness of the mechanical system is usually inadequate. Frequencies of over 100 cps are not faithfully reproduced by almost all routinely used ink-writers. In recent years, it is true, modified pen recorders have been produced that have proved to be efficient for most experiments.

The most accurate and elegant technique which should certainly be available in all emg* laboratories soon is continuous-strip photographic recording on either positive paper or negative film. As in our apparatus, many channels may be recorded on the same film as it is moved continuously past the open shutter of the

* Hereafter, the adjective electromyographic will be abbreviated to emg and the nouns electromyograph and electromyogram to EMG.
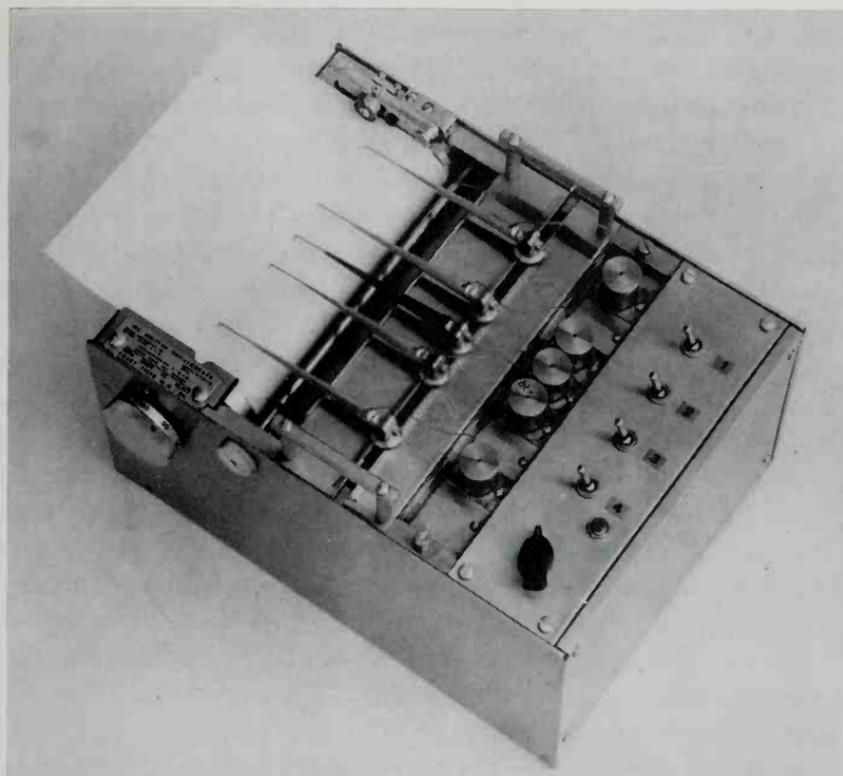
FIG. 32. One model of an ink-writing recorder suitable for simple kinesiological (but not clinical) EMG's. (Photo through courtesy of Grass Instrument Co., Quincy, Mass.)

linagraph camera. Direct recorders that produce immediate photographic paper records are now available and can be adapted quickly to any presently used amplifier system. The light-beam galvanometer recorders described in the Appendix (p. 366) are by no means the only ones available.

Routine motion-picture "frame" photography of the face of the cathode-ray tubes (as contrasted with our linagraph recording) has only a limited usefulness in kinesiological studies but may be combined with simultaneous "movies" of the subject's movements by split-frame photography. Various ingenious motion pictures have been produced in this way, but the technique is not

flexible enough for ordinary use. The techniques of Vreeland
et al. (1961) and Perry *et al.* (1966)* are noteworthy.

During 1966 our laboratory devised a novel technique of com-
bining colour motion-picture photography of the foot while walk-
ing with simultaneous magnetic-tape recording of the signal
from single channels of our 6-channel EMG. The new device is
an inexpensive camera (and companion projector) that uses 8 mm
film with a magnetic sound track on its edge. Instead of sound,
we record the output of the amplifiers. This can then be played
back on an oscilloscope in exact synchrony with the 24 frames-
per-sec film. Modified, the technique probably could be used for
synchronous recording of several channels.

Evaluation of Records

Evaluation of the recordings, whatever their type, is the most
abused part of electromyography. Part of the difficulty stems from
the use of poor records and part from inexperience. Records can
be improved, of course, and experience gained. Nonetheless, one
should consider carefully the reputation of the author of an elec-
tromyographic paper (or of the laboratory in which he is being
trained) before evaluating his results and conclusions.

Evaluation of any record is, of necessity, of two types—quanti-
tative or qualitative. Many investigators have confused these two
classes while others have assumed that any but quantitative re-
sults are not reliable. Most electromyographic records must be
considered by both criteria and, although this approach imposes
a discipline that quantitative results alone appear not to demand,
it is more reliable.

Many attempts have been made to make electromyography
purely quantitative. For example, integration of the electrical
potentials mechanically or electronically has been used (see be-
low). Bergström recently (1959) has claimed that the simple count-
ing of spikes is a quantitative reflection of the amount of muscular
activity, and we are presently trying to confirm his claim which
appears to be true within narrow limits.

* Unpublished. Rancho Los Amigos Hospital, Los Angeles, California.

Experience has shown that the easiest and, in most cases, most reliable evaluation is by the trained observer's visual evaluation of results colored by his knowledge of the technique involved. Indeed, not only are the number of spikes a factor but the amount of superimposition (summation) of spikes, and their height and type, are important too. We may classify, after some experience and training, the activity reliably into various levels, e.g., nil, negligible, slight, moderate, marked and very marked. Such a classification has proved extremely practical. Furthermore, when arbitrary units are assigned to each class (e.g., 0, $\pm$, $+$, $+$ $+$, $+$ $+$ $+$ and $+$ $+$ $+$ $+$, respectively) tabulation becomes simple. In our hands this technique has eventually proved the most useful and least fraught with self-deceptive pseudo-quantitation. For evaluating recordings on EEG recording paper, a simple viewing of the "tracing" is usually adequate. With linagraph film we use a film enlarger of simple design when needed or enlarge and print selected portions of the film.

Integration of EMG Potentials

Inevitably at some stage in their investigation, workers in electromyography become dissatisfied with qualitative analysis of records and turn (temporarily) to integration of potentials or other techniques as a solution. Integrators are electronic devices which can produce, when the emg or any other potentials are fed into them, an arbitrary quantitative figure derived from the variables of amplitude, frequency and spike shape. Various integrators are available since they are widely used in other electronic applications.

In the four or five years since the first edition of this book, integrated EMG's have become more widely used and the initial scepticism about their reliability has given way to cautious acceptance. There are many applications where integration of the output may be preferred (Tursky, 1964).

Its greatest dangers lie in: (1) failure to discriminate between artifacts and unit potentials (where naked-eye examination of standard records is superior), and (2) the self-deception of novices who think they can compare the integrated potentials from one

channel with those from another. One should always bear in mind that one can only compare the levels of the integrated curve with parts of the same curve.

The chief virtue of integrated outputs is the convenience of an immediate numerical read-out. Further, such output may be fed directly to automatic devices and requires no intermediate human interpretation. This great virtue must not blind us to the shortcomings of integration when it is used unwisely, as often it is (Grossman and Weiner, 1966).

The first useful information produced by integration of the emg potentials resulted from the work of Bigland and Lippold (1954a) who showed that integrated potentials vary directly with the strength of a contraction in a muscle. These workers had earlier shown that mechanical integration with a planimeter (such as used by geographers) was equally effective though much more tedious (Lippold, 1952). A promising new technique of "mean voltage recording" (Rosenfalck, 1960) may prove very useful in the future. Another recently described technique based on electronic counting of spikes (Close *et al.*, 1960) also shows much promise.

Vector Analysis

Pauly (1957) attempted to apply to muscle potentials vector analysis with a cathode-ray oscilloscope in the manner of vector electrocardiography. No special virtues are apparent or were claimed for this technique and it has been largely ignored in electromyography.

Microvibrations

If one applies suitable mechanical transducers to the surface of the body, a summation of tiny mechanical oscillations can be amplified and recorded. These bear a rough resemblance to EMG's; indeed the main source of the vibrations comes from muscular contraction (Williams, 1963). But other sources cause vibrations too, such as vascular pulses, phonics caused by the heart beat, etc. When integrated EMG's and integrated micro-

vibrations are recorded over the same contracting muscle there is often a remarkable similarity between the two (fig. 33). The technique deserves wider investigation for in some applications it may prove to be preferable to electromyography.

Shielded Rooms

Much good electromyography is done in ordinary rooms. Often, however, extraneous electromagnetic and electrostatic interference creates chaos in the amplifiers and recorders. Subjects, cables and the apparatus all may act as antennae for radio signals and the ubiquitous electromagnetic effects of power lines. Ideally, the laboratory should be isolated from such effects.

A useful provision in any laboratory is an isolation transformer which feeds all the outlets in the laboratory. This is simply a one-to-one transformer. Its cost is so small that the investigator soon forgets his indebtedness to its silent work.

Sometimes all efforts fail unless a shielded room is used. Some very complex types are built, sold and advocated. They are usually too complicated, too small and too expensive. In new
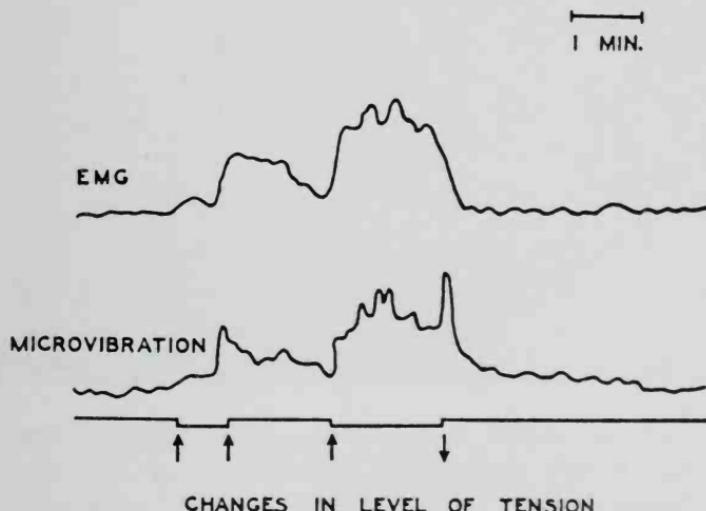

FIG. 33. Comparison of amplitude-integrated EMG and microvibrations over same muscle-group. (From Williams, 1963.)

Fig. 34. An inexpensive, sectional copper-screened cage (Anatomy Department, Queen's University). The door is left open here, but normally should be shut.

buildings a room can be completely shielded by incorporating copper screening in its walls, floors and ceilings. In my experience few such rooms are perfect.

A very serviceable, inexpensive shielded cage may be built which is quite good for most uses. It consists of a wooden frame covered with copper or bronze mosquito-screening, which is grounded or earthed. Ideally it is made sectional to allow rapid dismantling. Its floor is raised and of course the screening must be continuous across the under surface of the floor as everywhere else (fig. 34). No great inventiveness is required to design a cheap but first-rate enclosure of this type that fits local needs.
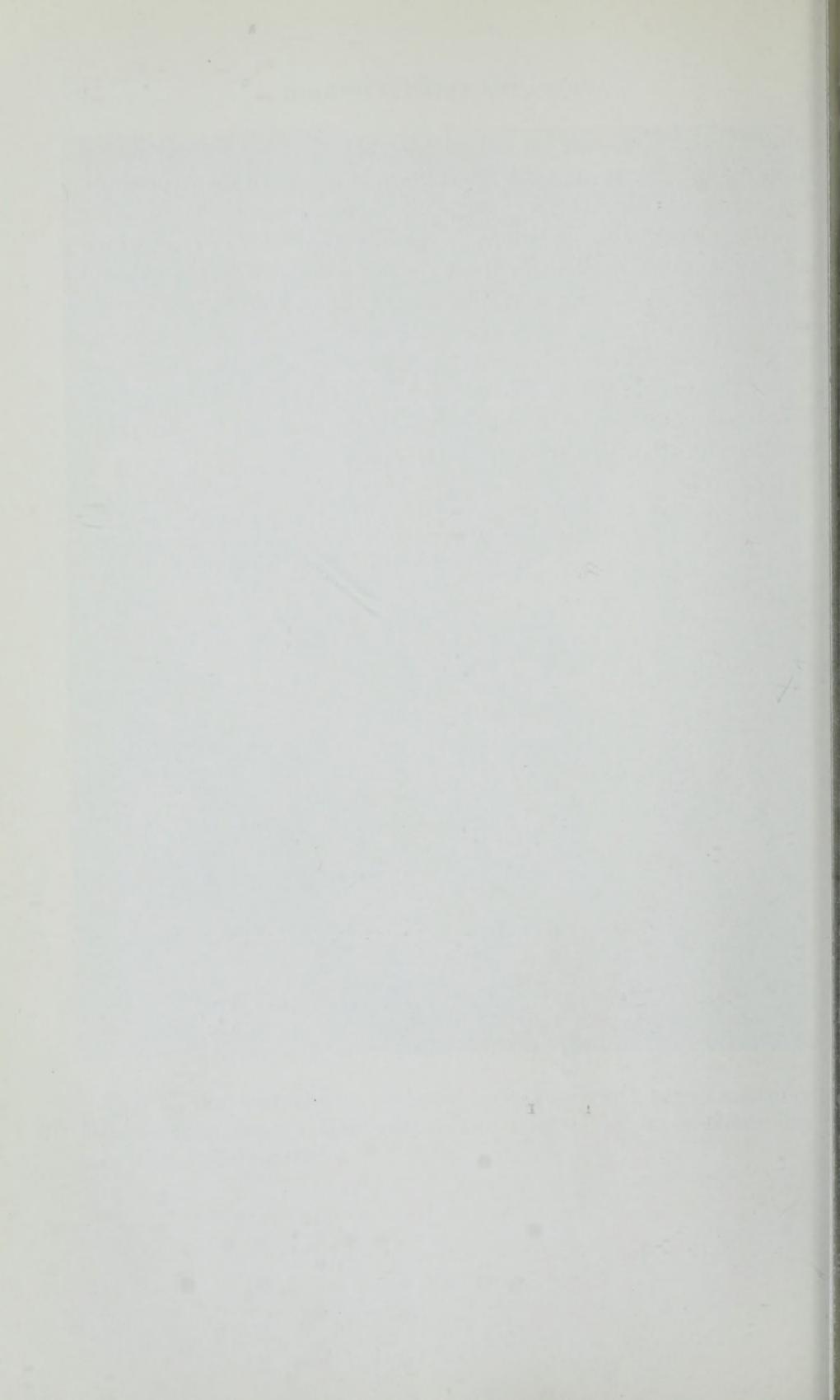
Synthetic EMG Waves*

W︎HEN a muscle is tensed, an emg wave of muscle action potential is a summation of anywhere from a few to a great many signals (emf impulses) arising from the random firing of motor units. If the tension is increased, the emg wave changes, tending to become greater in amplitude.

It is very simple, and no doubt appealing, to think that if a certain muscle tension gives a certain electrical effect at the surface, then, doubling that tension should double the surface effect by making the wave's amplitude twice as great. As we shall see the phenomena are actually so much more complex than that, that such "reasoning" is not only not helpful—it is useless and misleading.

Can a graded series of increasing tensions and the corresponding series of emg waves be correlated, so that some characteristic of the wave will serve as an indirect measure of the muscle tension?

* This chapter was written in its entirety by my good friend, A. D. Moore, Professor Emeritus in Electrical Engineering at the University of Michigan. Because of its unique nature, it is reprinted here (slightly revised) from the American Journal of Physical Medicine with the permission of the publishers (Williams & Wilkins Co.) and the editor (H. D. Bouman).

The attempt to predict such a correlation presents its difficulties. At a lower tension, the wave represents an unknown number of unknown components; at a higher tension, a larger number of still-unknown components. This at once says that there is no way of looking at the wave to find out "what happened." If the components are unknown, how can we make sound predictions about the wave?

Moreover, there appears to be no hope of ever untangling the problem, working from direct physiological research alone. A complete understanding of just one case would require that for a given tension, not only would the emg wave be recorded—but also, every component of it due to every motor unit involved, would simultaneously be recorded. This is impossible today; and it bids fair to remain impossible, except for the very simplest cases.

For gaining insight in these matters, the opposite approach, and the one attempted in this chapter, is to begin with known components, summate them somehow and see what kind of wave is built up. If we knew (as we do not) all about all of the individual motor unit emf components in an actual case, as to shape, amplitude, number and distribution, we could synthesize a wave that would precisely duplicate the actual measured wave. A series of these studies, representing graded increasing tensions, would tell us a great deal. The ideal, complete study just described cannot be made for lack of sufficient information about components. However, synthesis on a simplified basis, made by adopting simple components, can be accomplished. That is the approach used herein.

The Impulse Adopted and the Period

A single fibre of a single motor unit is prone to give a biphasic impulse. The several or many fibres in the unit may somewhat overlap their impulses, due to different lengthwise locations of the motor endplates, and different times of nerve stimulus arrivals. Thus the motor unit impulse may be more complex than a simple, symmetrical biphasic wave such as is shown in figure 35,a. Also,
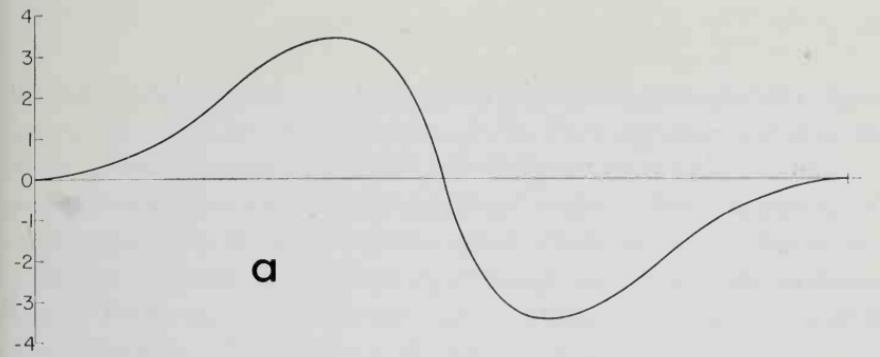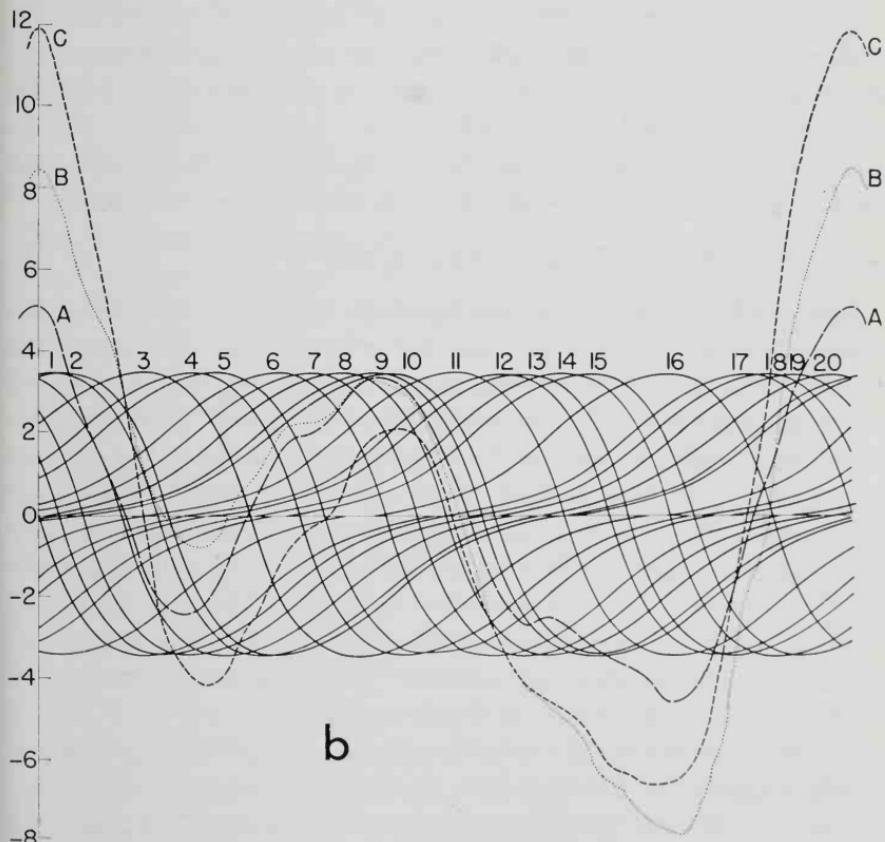
FIG. 35. Impulse adopted, and a randomly distributed population. *a*, The adopted impulse. Its time length is called a period. *b*, The randomly distributed population of Q = 20 impulses per period. Wave A is the summation. For waves B and C, see text.

motor units nearer to the electrodes will give larger impulses than those farther away.

Even so, this study had to be kept to a simple, basic level. With one exception taken up later, all synthesized waves herein were made up of identical components: copies of the figure 35,a impulse. Moreover, this is not a physiologically-derived impulse; instead, it is an arbitrary symmetrical curve, assumed to be sufficiently representative of the real thing. The ordinates are given in the appendix to this chapter on page 70.

If nothing informative comes out of such a simplified study, nothing could come from a more realistic and complicated study; but if the simplified study is informative, encouragement is given for expanding this line of attack.

The adopted impulse was drawn to an arbitrary scale. Its time length, on the horizontal axis, is herein called the *period*.

What Kind of Wave Can Be Anticipated?

If a lot of these impulses, randomly distributed, are summated, what would we anticipate as to the character of the resultant wave? And if, then, the number of impulses is doubled, how would this wave compare with the first? These questions were put to a number of experts working in electronics, communications and statistics. No helpful answers came. This is a problem that still defies analysis, even though able men are interested in it and working at it. Among those approached, a goodly number made an almost automatic guess at one answer to the first question: there would be a large degree of cancellation. On further thought, this guess was usually withdrawn. Further guessing was withdrawn, too. This is unfamiliar territory.

As to cancellation, this would certainly dominate if, instead of random spacing of the impulses, equal (uniform) spacing is used. A study of this, for the figure 35,a impulse, was carried out, using 20 impulses per period. The small residue wave left in the summation had a maximum amplitude of only 0.23, as compared with the impulse maximum of 3.42.

Random distributions will of course give cancellation effects

at some places, and pile-up effects at others. This helps one to appreciate the fact that there just is no way of predicting the wave characteristics. To make any progress, a population of component impulses must be added up to get a wave; likewise for larger populations to get more waves. Only then can inter-comparisons be made, and possibly, relationships be found between some wave characteristic and the population of impulses that produced it.

Preliminary Trials, the Population, a Showcase Example

"Population," having the symbol Q herein, means the number of impulses per period. A template was made to fit the impulse shape, making it easier to draw many overlapping impulses. A few trial cases of differing populations were carried out the hard way (graphics-plus-arithmetic) to get the summation waves. They seemed to show promise.

A "showcase example," figure 35,b, was then made up, also the hard way. It has a randomly distributed population of Q = 20. A roulette wheel type of scheme (tossing a round disk up and catching the edge) dictated the random locations of the impulses. Curve A is the summation wave. Impulse No. 15 was then deliberately selected for removal—to have the largest effect on the peak. Curve B resulted, giving a higher peak for 19 impulses than we had for 20. For further emphasis, the missing impulse was deliberately put back in to coincide with No. 20, giving Curve C with a still higher peak. (This synchronizing of two impulses will be brought up again later.)

For Curves A, B and C, in that order, the peaks are 5.0, 8.4 and 11.9. In the same order, the RMS (root mean square) values are 2.8, 4.7 and 5.2. One lesson to learn here is that, since random distribution of impulses may sometimes yield any of these effects, a wave train as short as one of these periods cannot be expected, for Q = 20, to yield anything like a standard, reliable summation wave. Neither will a far larger population—as will be seen when computer-derived waves are taken up.

The large amount of work involved in creating figure 35,b

clearly showed that any real progress from there on would have to bring the computer into the picture.

Computer Data, Plotting the Wave

The adopted impulse, figure 35,a, was readied for the IBM 7090 computer by reading 101 ordinates, evenly spaced (see appendix to this chapter, p. 70). The computer was ordered to use the ordinates, to randomize and sum up a population of $Q = 20$ impulses, and to do it for 20 periods. Some 2000 numbers came out, as ordinates of the summation wave. Since the first period was a get-ready period and incomplete, it was discarded, leaving 19 usable periods.

To save a great deal of work, only every tenth number from the computer was read and plotted in figure 36,a. This is why the wave which otherwise would have smoothly rounded peaks, was drawn with broken lines. The compromise makes no essential difference in the findings to be described later. The dash lines, figure 36,a, show the amplitude of the impulses.

Higher Populations and Comparison by Inspection

The available computer time was used up in the $Q = 20$ run. However, a $Q = 40$ wave could be obtained (figure 36,b, left) by adding the first 9 periods of figure 36,a to the next 9 periods. This was done by long-hand methods. This derives a 40-wave in precisely the same random way that a computer might happen to produce it directly. Also, another 40-wave (figure 36,b, right) was obtained by adding the 20-wave's first 9 periods to the last 9 periods. By the same kind of manipulation of the 40-waves, the 80-wave (figure 36,c) was produced.

Three observations can at once be made from visual inspection alone. First, the greater the population, the greater the amplitude. Second, the average frequency, indicated by number of axis crossings in 9 periods, remains essentially unchanged by population increase. Third, the general characteristic or appearance of the wave (except for amplitude) seems to be unchanged by population increase. Inspection can lead to such an opinion about the
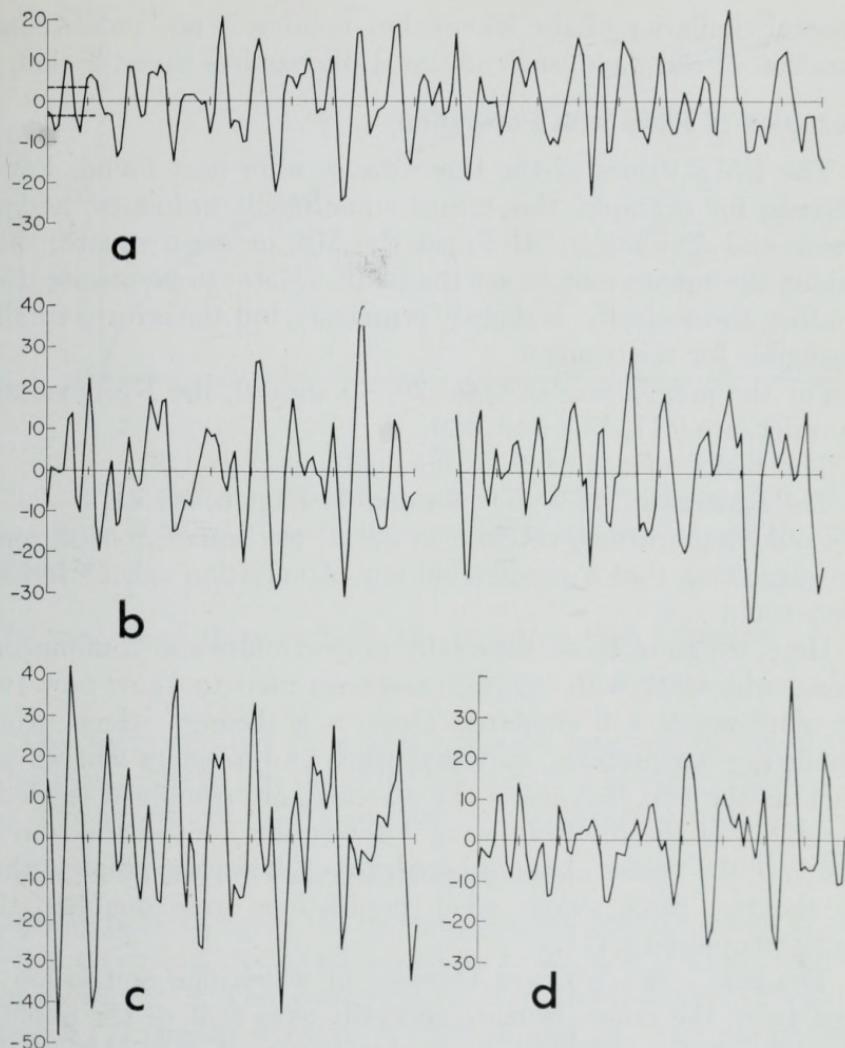
Fig. 36. Synthetic emg waves from computer. a, Q = 20 impulses per period, for 19 periods; the dash lines show the amplitude of the impulses. b, Q = 40, for 9 periods, left; and another 9 periods, right. c, Q = 80, for 9 periods. d, Hybrid wave, made by using the first 9 periods of (a) at full amplitude, plus the next 9 periods of (a) at half amplitude.

general similarity of the waves, but opinion is not proof. Some
function of the wave, such as the RMS requires investigation.

Variation of RMS with Population

The RMS values of the three waves were next found. For 9
periods, for example, this meant squaring 91 ordinates, adding
them, and dividing by 91 to get the MS, or mean square; then
taking the square root to get the RMS. (Note: to be precise, this
routine, theoretically, is slightly erroneous; but the error is totally
negligible for this study.)

For the populations of Q = 20, 40 and 80, the RMS values,
in order, are 9.17, 13.4 and 18.9.

The RMS ratio, 13.4/9.17, for doubling Q, is 1.46.

The RMS ratio, 18.9/13.4, for doubling again, is 1.41.

Could these ratios, so close to 1.414, the square root of two,
be suggesting that a predictable law of variation exists? Indeed
they could.

Here, we go to those, especially in electronics and communica-
tions, who work with "noise," and who need to know how two
or more noises will combine. There is a theorem which, when
applied to our problem, says that when two irregular emf waves,
such as the two that made the 40-wave, are combined (added),
the RMS of the resulting wave is the square root of the sum of
the two MS values of the original waves. This law predicts that
in the two cases above, when populations were doubled, the
ratios should be 1.414.

The law is not confined to cases in which one population is
just twice the other. It more generally says that as the popula-
tion of impulses, all alike, is steadily increased, the RMS of the
summation wave varied with the square root of the population.
That is,

$$RMS = K\sqrt{Q}$$

where K is a constant. If we let each of the three populations
above, and their respective RMS values, determine the constant,
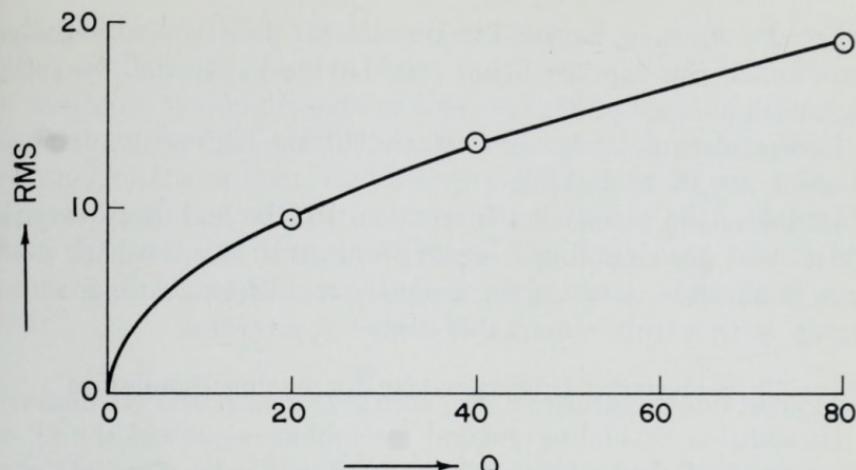the values of K, in order, are found to be 2.05, 2.13 and 2.11.

Fig. 37. Variation of RMS with population. The curve has the equation, RMS = 2.09 Q. The three points are from the waves for Q = 20, 40 and 80.

The average of these is 2.09. The equation then becomes:

$$RMS = 2.09\sqrt{Q}$$

The curve plotted from this equation is given in figure 37. Also plotted there are the three RMS values for Q = 20, 40 and 80. The agreement, for these purposes, is virtually exact.

Variation of Higher Peaks with Population

Going back to figure 36, the four highest positive peaks in the first 9 periods of the 20-wave add up to 73, and the four highest negatives, to 78. The average is 75, in rounded figures. Treating the next 9 periods likewise, we get 70 and 68, with an average of 69. The average for 18 periods is 72. Divide by 4, and we get the high-peak average of 18.

For the 40-wave, left, 9 periods, the four high positives add to 108, the negatives to 103, with an average of 105. For the 9 periods at the right, 90 and 113, which average to 101. The average for 18 periods is 103. Divide by 4, and get a high-peak average of 26.

For the 80-wave, we get 143 and 158 for positive and negative peak sums, the average being 150. Divide by 4, and we get a high-peak average of 37.

Recapitulation: for Q = 20, 40 and 80, the high peak averages, in order, are 18, 26 and 37.

Doubling the population from 20 to 40, the high peak ratio is $26/18$ = 1.44. Doubling it again from 40 to 80, the high peak ratio is $37/26$ = 1.42. Again, a square-root-of-two ratio is showing up, with a truly remarkable degree of precision.

Wave Characteristics Unchanged by Increasing Population

In addition to finding general resemblances among the Q = 20, 40 and 80 waves of figure 36 by visual inspection, we now have three measures of mutual consistency. First, the average frequency, indicated by the number of axis crossings, is much the same in all. Second, the RMS varies with the square root of Q. Third, the higher-peak average also varies with the square root of Q. These measures seem strongly to suggest that the more important characteristics of the wave are not changed by population increase.

Now, what about population higher than the highest (Q = 80) used herein? In figure 35,b, the component impulses of a 20-wave are seen. Imagine how this chart would look if turned into an 80-wave: it would look extremely crowded. Then, what if a chart were made for *four times* that population—that is, for a 320-wave? It would look almost black. When put this way, one is bound to wonder if such far higher populations would continue to turn out waves of the same general characteristics as found for the lower populations.

But there is another way to think about it. Instead of worrying about a vast number of *impulses* per period, we can instead concentrate on *waves*. We have already found that when four 20-waves, figure 36,a, are added up randomly to produce 80-waves, figure 36,c, the two *waves* have the same general characteristics, and are related by definite laws. It follows that if four 80-waves are randomly added to make 320-waves, we will

again come out with the same general kind of wave, again related in the same ways to those that gave it birth. This is one of the most striking results of this study. It should of course be verified by further work; but the argument above strongly indicates, for the present, that a low population of 20 and a vastly higher population of 320 (or even much higher than that) will turn out waves of the same general characteristics, with RMS values and high-peak amplitudes varying with the square root of Q.

Preliminary Discussion of Motor Unit Recruitment and Behaviour

Up to now, no attempt has been made to match muscle force with impulse population and wave properties. To get the thinking organized, let us temporarily adopt two assumptions: first, that muscle force is proportional to the number of motor units recruited; and second, when a unit is recruited, it instantly produces its maximum tension or force, and continues to do so. These assumptions are wrong, and will be abandoned later, but they will help to organize the picture.

The outcome is that impulse populations are proportional to the graded forces required of the muscle: if force is doubled, population is doubled. We have found that wave RMS varies with the square root of Q. The final outcome is that force varies likewise. That is, these assumptions predict that the RMS of the emg wave varies with the square root of the force.

If this were true, it is convenient to re-interpret figure 37. For a large muscle, think of three of the numbers on the horizontal scale, 20, 40 and 80, as now meaning pounds; then the curve gives (relatively) the increasing RMS values of the waves. This, we note, is far from being a linear (proportional) variation.

Let it be made plain at this point that this analysis is not in any sense directed toward supporting either a linear, or a nonlinear, variation. And now, the above too-simple assumptions must be replaced by something more nearly in accord with the facts.

Recruitment and Motor Unit Response to Motoneuron Stimulus Frequency

Here, Ruch *et al.* (1963) and those they cite will be followed. A motor unit consists of anywhere from three to hundreds of muscle fibers, all stimulated by a motoneuron, and all contracting when a stimulus comes. If a single stimulus arrives, there are two outward, or externally measurable, responses. First, the fibre membrane fires, giving an electrical impulse to be picked up by the electrodes; second, mechanically, a twitch occurs, rising to a maximum twitch force and falling off again, and of much longer duration than the impulse. If two stimuli arrive close enough together, the two twitches fuse somewhat, giving a higher maximum; and with three, somewhat higher yet, and so on. If stimuli continue to arrive, and fast enough, fusion of twitches becomes virtually complete, giving a quite steady maximum force typically four times that of a single twitch maximum. Although the twitches thus overlap and fuse, the electrical impulses from the fibre firing never overlap.

According to Adrian and Bronk (1928, 1929): "During voluntary contraction the discharge of single motoneurons varied between 5 and 50 impulses per second as the contraction increased from light to maximal effort." Again quoting Ruch *et al.*: "As more force is required, three things happen in an overlapping sequence: (i) more motor units are activated (recruitment); (ii) the active motor units discharge more frequently but not rapidly enough for muscular summation (i.e., the response is subtetanic); and (iii) with further increase in frequency, the motor unit twitches summate to form a tetanus." Thus, not only are there overlapping stages; but, as a unit is recruited, it joins in at first with twitches, and ends with a steady contraction force of about four times the maximum of a twitch.

Hypothetical Motor Unit Recruitment Schedule

The table in figure 38 shows one attempt to construct a schedule of recruitment and envisage the outcome. First, it was assumed that the range of 5 to 50 motoneuronal stimuli per second could

Group		A	B	C	D	E
		q means population coming from a unit group f means force coming from a unit group				
		Force levels, increasing to the right, from one column to the next.				
1	q	64	64	64	64	64
	f	6	6	6	6	6
2	q	32	64	64	64	64
	f	5	6	6	6	6
3	q	16	32	64	64	64
	f	4	5	6	6	6
4	q	8	16	32	64	64
	f	2	4	5	6	6
5	q	4	8	16	32	64
	f	1	2	4	5	6
	Q	124	184	240	288	320
	$\sqrt{Q}$	11.2	13.6	15.5	17.0	17.9
	F	18	23	27	29	30

Fig. 38. Hypothetical schedule for motor unit recruitment, employing five equal groups of motor units.

be replaced for convenience by a 4 to 64 range. This in turn was divided into the series of 4, 8, 16, 32 and 64 stimuli per second. It was further assumed that in the same order, the corresponding motor unit forces would be proportional to the numbers 1, 2, 4, 5 and 6. (These are seemingly reasonable values that were adopted; others would no doubt exercise a different judgment and adopt other values.)

Next, the muscle was divided into five equal groups of motor units, to be recruited in overlapping sequential order (Groups 1 to 5), giving rise to five Force Levels (columns A to E). For example (see table) at Force Level A, it was assumed that Group 1 had all of its motor units at maximum, with 64 stimuli per second arriving. For simplicity, q = 64 stands for two things:

rate of stimuli and also the emg impulses contributed to the total population of Q. A group force of f = 6 is attained, this being the group's contribution to total muscle force F. Group 2 is recruited and is well along, at q and f of 32 and 5. Group 3 is less further along, 16 and 4, and so on. Total Q, 124; the square root being 11.2; and total F, 18. Inspection of the table shows how the groups are increasingly activated for higher force levels. In Force Level E, all groups have achieved maximal force. The outcome, in part: Q ranges from 124 to 320, with square roots ranging from 11.2 to 17.9; and total force F ranging from 18 to 30.

How Does the RMS of the EMG Wave Relate to Muscle Force?

If, from the table, the square roots of Q are plotted against the respective forces F, a straight line from the origin can be drawn to fit the points, the worst disagreement being about 6%. Since, earlier herein, it was found that the RMS of a synthesized wave varied with the square root of Q, it follows that in this case, we have found the RMS to vary directly with (proportional to) force. The table covers approximately the upper half of the total muscle force range (18 to 30). Presumably, a recruitment table could be devised for the lower half, to give the same law of variation.

Experimentally, de Vries (1965) has found essentially this result for the biceps brachii. Do these essentially identical results (de Vries' and the foregoing) validate each other? Emphatically not. The present study can neither prove nor disprove a linear variation, for it is a devised, or rigged, set of values seen in the table. A different scheme for bringing the five groups into action, can lead to quite a different outcome. Before arriving at this table, the writer tried various other combinations, and most of them tended more nearly to let Q vary with F, instead of Q-squared varying with F. When Q varies with F, the square root, representing the RMS value of the wave, by no means rises as fast as linearly. The curve bends over (see again the re-interpretation of figure 37).

Something like what is shown in figure 38 may well happen.

SYNTHETIC EMG WAVES

But it is difficult to believe that a muscle would follow through in such a regularly-advancing manner, as force builds up. Even if the advances made by the groups occur like this, it does not follow that the groups should be of equal size. Moreover, the build-up in Group 1 may, for all we know, follow a schedule quite different from that of a later group. And even if, by some miracle, the table holds for one striated muscle, it may not hold for another. Evolution has a tidy way of warping a particular muscle to fit the needed requirement, and seeing to it that it does its job to the best advantage of the organism—and not to give pleasure to those of us who like to admire an orderly series of numbers.

Two kinds of skeletal muscle occur in many vertebrates. Red muscle, typically slower, manages the sustained-contraction jobs. White muscle, faster, handles the quick-motion duties. In emg work done on animals, this distinction demands close attention, for the details of recruitment may turn out to be different in the two; and if so, the RMS-force relationship may differ.

In man, the highest vertebrate, we find a remarkable exception: his skeletal muscles are a mixture of the two kinds. Tokizane and Shimazu (1964) have done what seems to be a superb job at showing that these two sets of motor units operate under different controls, and respond in different ways; and that "every muscle differs from every other in these respects."

The linear variation of RMS with force found by de Vries is backed by what appears to be careful and accurate techniques. However, it does appear that other workers have definitely found a less-than-linear rate of rise for some muscles, and with a tendency for the wave to change little in amplitude as maximum force is approached.

The purpose of this theoretical treatment is to do what it can to illuminate the subject and assist some of the thinking that should go along with research in EMG. It may well turn out that after carefully contrived techniques have been applied to different muscles by an adequate number of workers, various muscles will be found to have different ways of responding to

demand; and that the RMS (or other measure) as related to force will have to be settled on the individual muscle basis.

Random *vs.* Synchronous Motor Unit Action

In the low end of the force range, a muscle would appear to have relatively few motor units activated, with many of these yielding only twitches or poorly fused twitches. If they operated synchronously, jerkiness would ensue. Instead, in acting at random, the overlapping of the little forces gives a steady force in isometric contraction, or smooth control in movement. High in the force range, most of the motor units that can be recruited by conscious effort are at maximal, producing steady forces. Here, steadiness of total force and control of movement would depend much less on random action.

This opens the way for suggesting that some degree of synchronization may enter in, at high force, for some muscles. First, in a way as yet unknown, it may happen automatically; or second, it may be built in to give an advantage yet to be discovered. The point is that if, as force demanded rises, there is a *small* shift from complete randomness toward synchronism, a relatively large increase in RMS and in high-peak ordinates would take place. This is seen by returning to the showcase example, figure 35,b; where, to repeat, in moving only one impulse out of 20 to make it coincide with another, the high-peak rose from 5 to 11.9 and the RMS rose from 2.8 to 5.2. Such a shift would tend to make a muscle's RMS rise more nearly linearly with force, when otherwise it would rise less fast. Thinking in terms of the table showing the Recruitment Schedule (figure 38), this shift would not change the Q-values, but certainly would change the maximum amplitudes and RMS values. This offers one more item to think about in planning emg research. Possibly, patient work with implanted electrodes will prove, or disprove, a shift.

Then, there is the opposite possibility: that a small degree of synchronism is present in the intermediate range of some muscle, which drops out at near-maximal effort. This could account for

what happens when the EMG refuses to rise much, as the force increases at near-maximal.

Non-uniform Populations

The actual emg wave is, of course, a summation of impulses of all sizes, due to nearness or farness of electrodes to motor units. That is, it has non-uniform populations. To look into this aspect a little, one case was carried through. Figure 36,d shows a wave made by hybridizing. It is a hybrid of $Q = 40$, made up of the first 9 periods of $Q = 20$; plus the next 9 periods of $Q = 20$, taken at half-amplitude values. We again see a general similarity to the other waves.

More than that, its RMS can be predicted as the square root of the MS values of the two waves that were combined. The prediction is 10.35 for the RMS; the computed, from the wave, is 11.0, which checks to within 6%.

This seems to encourage the idea that if these studies are computer-extended to combine several populations graded as to impulse amplitudes, the simple relationships brought out in the present study might still prevail.

Synthesized Wave's Resemblance to Actual EMG Wave

Some emg workers may not be accustomed to waves that are as magnified and stretched as those in figure 36. When the first
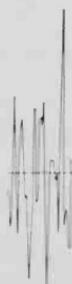
FIG. 39. Resemblance of synthetic wave to actual emg records. This is the first 5 periods of the figure 36, *a* wave compressed.

5 periods of the 20-wave, figure 36,a, are squeezed down, we get the rendition in figure 39. It is indistinguishable from any number of actual waves now on record.

Limitations of the Study, Further Studies

It must again be emphasized that this is a simplified and limited study. Simplified, by dealing with a series of uniform populations of impulses, except in one case; and perhaps too limited in scope to warrant drawing final conclusions. The least that should be done is for someone independently to repeat the study, to find if the same laws and relationships again show up. Preferably, the repetition would extend for considerably more periods.

If that work is done, and this study is verified, then a more expanded study would be warranted, to include (1) several amplitude-graded but otherwise like-shaped populations of impulses, (2) populations of impulses alike as to amplitude but different as to shapes and (3) a combination of (a) and (b). After that, other variations might be justified.

APPENDIX TO CHAPTER 3

The *ordinates* as used in the computer, for the first half of the adopted symmetrical impulse, are given here in order, after first having been multiplied by 100 to avoid putting in decimal points:

0, 1, 3, 6, 10, 12, 18, 23, 30, 35, 41, 50, 56, 65, 73, 83, 95, 108, 120, 135, 150, 166, 182, 200, 215, 231, 250, 265, 279, 290, 302, 312, 320, 328, 334, 339, 341, 342, 342, 340, 333, 324, 310, 291, 270, 243, 220, 170, 120, 60, 0.

Muscular Tone, Fatigue and Neural Influences

MOST neurophysiologists now agree that electromyography shows conclusively the complete relaxation of normal human striated muscle at rest (Clemmesen, 1951; Basmajian, 1952; Ralston and Libet, 1953). In other words, by relaxing a muscle, a normal human being can abolish neuromuscular activity in it. This does not mean that there is no "tone" (or "tonus") in skeletal muscle, as some enthusiasts have claimed. It does mean, however, that the usual definition of "tone" should be modified to state that the general tone of a muscle is determined both by the passive elasticity or turgor of muscular (and fibrous) tissues and by the active (though not continuous) contraction of muscle in response to the reaction of the nervous system to stimuli. Thus, at complete rest, a muscle has not lost its tone even though there is no neuromuscular activity in it (Basmajian, 1957b).

In the clinical appreciation of tone, the more important of the above two elements is the reactivity of the nervous system. One can hardly palpate a normal limb without causing such a reaction. Therefore, the clinician soon learns to evaluate the level of "tone" and it may seem of little consequence to him that the

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muscle he is feeling is, in fact, capable of complete neuromuscular inactivity. In spite of this, he would be surprised to learn that an experienced subject can simulate hypotonia or even atonia of lower motor neuron disease and successfully deceive—if only for a brief period—the most astute physician.

During the course of various electromyographic studies on spastic patients and spastic rabbits, I was impressed with the relative ease with which most spastic muscles also can be completely (though only temporarily) relaxed (fig. 40). Magoun and Rhines (1947) and Hoefer (1952) and others have also noted and commented on this, and it has been demonstrated by Kenney and Heaberlin (1962) in spastic children lying quietly, and by Holt (1966) also.

In thousands of electromyograms on normal human muscles, there has been complete and almost instantaneous relaxation when
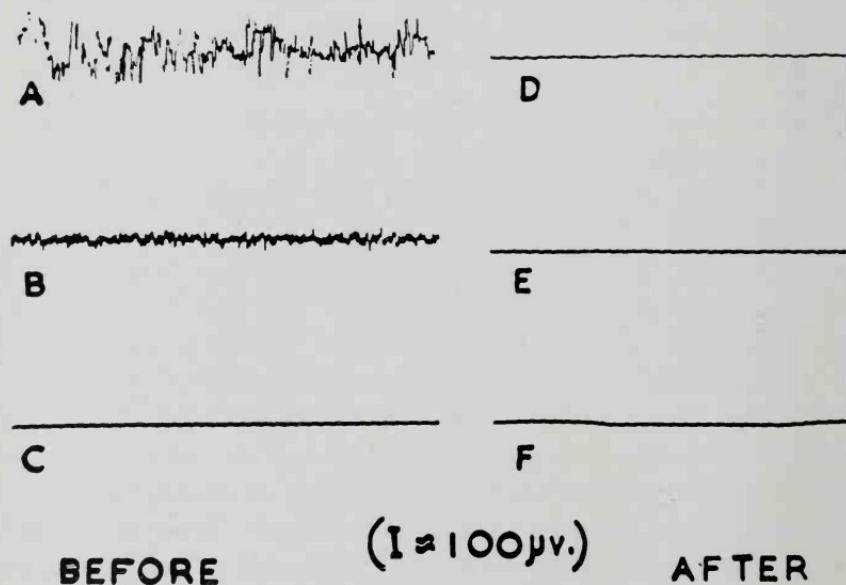
FIG. 40. Tracings A, B and C showing varying degrees of emg activity at rest in the spastic quadriceps of three different patients with severe spasticity. Many subjects can be quieted down to the "emg silence" of C without drugs. (Tracings D, E and F show the results of intravenous chlorpromazine in the same three patients.) (From Basmajian and Szatmari, 1955a.)

the subject has been ordered to relax. However, a small number of normal subjects do have great difficulty in relaxing quickly. In no normal muscle at complete rest has there been any sign of neuromuscular activity, even with multiple electrodes. As Stolov (1966) puts it: "We can therefore conclude that no alpha motor neuron discharge is present in normal muscle at rest, but may be present during a stretch that is rapid enough to initiate a reflex response."

"Complete rest" requires some qualification. A normal person does not completely relax all his muscles at once. Reacting to multiple interoceptive and exteroceptive stimuli, various groups of muscles show rising and falling amounts of activity. Iris Balshan Goldstein (1962) showed that 16 muscle groups measured at rest were related to a general muscular tension: these were mostly in the limbs and neck. Only frontalis and left sternomastoid were unrelated. Anxious subjects were not greatly different from non-anxious ones—except for the very anxious types of persons who showed marked reaction to new stimuli. These findings occurred in both women and men. Goldstein (1965) showed later that hysterics and certain other neurotics have very little increase in muscular tension over normal persons. During sleep, tonus of most head and neck muscles falls off, but, according to Jacobson, Kales, Lehmann and Hoedemaker (1964) "trunk and limb muscles exhibit stable levels of tonic activity throughout the night."

Leavitt and Beasley (1964), in accepting the absence of emg potentials at rest as true relaxation, wondered whether such emg silence could be maintained while the muscles being recorded were passively stretched. Quite surprisingly, they obtained absolute silence in both flexors and extensors of almost all subjects whose knee joints were flexed and extended passively, regardless of whether this was done slowly or rapidly. Although they actually were more interested in reciprocal inhibition of antagonists during active movements (see p. 86), Bierman and Ralston (1965) reported similar findings. Obviously, subjects could relax consciously during a state when normal myotatic reflexes would be expected to occur.

In a series of experiments with normal rabbits we found that

if they were handled gently and firmly and the limbs placed and held in relaxed positions, the muscle being examined (generally the gastrocnemius or soleus) showed a rapid reduction of activity to *nil*. An experienced handler could get a rabbit to relax in a matter of seconds but any noise or other stimuli easily induced activity in the muscles.

Muscular "tone" is a useful concept if we keep in mind that at rest a muscle relaxes rapidly and completely. This has now been common knowledge among neurophysiologists for more than a decade. To repeat, tone is a function of the nervous system controlling muscle, but it also results from the natural elasticity of the muscular and fibrous tissue. The normal "feel" of the muscle is determined by its normal tissue turgor and its immediate reflex response to palpation. If one keeps one's hands off a resting normal muscle, it shows no more neuromuscular activity than one with its nerve cut. In fact, it shows *less* because the fibres of denervated muscle engage in many fine random contractions invisible through the skin but detected by electromyography as "fibrillation potentials." The muscles in lower motor neuron denervation actually exhibit very fine invisible contractions while normal resting muscles exhibit complete neuromuscular silence. (These fibrillations are not to be confused with fasciculation, the coarse contractions of motor units visible through the skin and also often called fibrillations by older neurologists.)

Where did the false concept of continuous neuromuscular activity during rest originate? Chiefly it seems to be a wide-spread misinterpretation of Sherrington's *postural tonus* (fig. 41). There is no denying that any muscle that is helping to hold the subject upright shows various degrees of activity. On the other hand, our group, among a number of others, has shown that not all the muscles of the leg need to be active in the upright position. That is, the human upright position allows many of the limb muscles to relax completely. Yet these muscles will immediately respond to any change endangering the loss of balance (see p. 151). The neural basis of much of the interoceptive stimuli that lead to rapid responses is unquestionably the gamma-loop system (Granit, 1964).
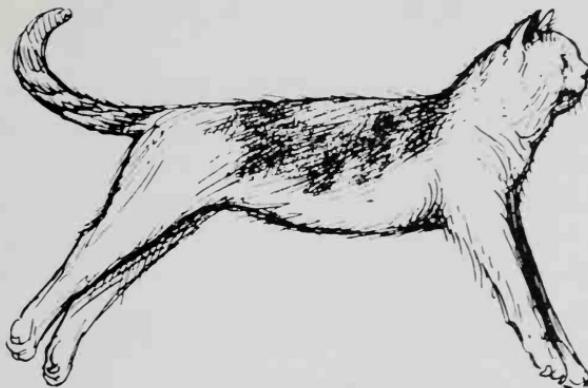
Fig. 41. Postural tone of decerebrate cat. (From Pollack and Davis, 1930.)

Spasticity

In another set of experiments we found that the spastic limb muscles of most human beings with lesions of the central nervous system could be relaxed completely (fig. 40). In the remaining spastic subjects the activity could be materially reduced, but, under the experimental conditions, complete relaxation was not obtained—probably due to the presence of considerable environmental stimuli (e.g., a well-lighted room, the activity of the investigators, apprehensiveness). In all spastic subjects, very slight stimuli (even conversation) causes immediate electromyographic activity. Similarly, the muscles of spastic rabbits can be completely relaxed, as we noted above, but much more careful effort is required on the part of the handler. As with spastic human subjects, the slightest stimuli causes marked activity which takes some considerable soothing to abolish.

Shimazu, Hongo, Kubota and Narabayashi (1962) confirmed our conclusion with the spastic and rigid muscles of patients with Parkinsonism. They found no spike discharges in resting muscles, but there was a greatly exaggerated stretch reflex.

The findings described for spastic human beings and rabbits at rest therefore are not surprising. While the increased tone is simply an overactive reflex contraction, the limbs can be relaxed com-

pletely, albeit with greater "effort" than that required by normal subjects.

An incidental, perhaps inevitable, result of our electromyographic studies of human spasticity and the effects of chlorpromazine (Basmajian and Szatmari, 1955a, 1955b), seems to have been the general adoption of electromyography for studying the effect of the newer relaxant drugs and other types of therapy (Brennan, 1959). In view of what has been already discussed, it hardly seems necessary to warn against a naive acceptance of "electromyographic" evidence if the only criterion used is the amount of the activity "at rest." Unfortunately some workers have already published such data.

Fatigue

Since its inception, electromyography has been used by some workers in the investigation of fatigue. I shall observe, at once, the traditional and necessary warning that fatigue is a complex phenomenon and perhaps a complex of numerous phenomena. The fatigue of strenuous effort is probably quite different from the weariness felt after a long day's routine sedentary work. Undoubtedly the following types exist: emotional fatigue, central nervous system fatigue, "general" fatigue and peripheral neuromuscular fatigue of special kinds.

Seyffarth (1940) showed that the increasing fatigue of prolonged voluntary periodical contraction of muscles of the forearm is accompanied by reduction of potentials. This is exaggerated by ischemia caused by a tourniquet. There is a diminution and variation in amplitude of the size of the motor unit potential (fig. 42). Loofbourrow's observation (1948) appears to agree. He concluded that reduction in mechanical response with fatigue during indirect supramaximal tetanization (in cats under anesthesia) is accompanied by a corresponding decrease in amplitude of emg potentials (fig. 43). An increased amplitude is always obtained by increasing the mechanical tension through stronger stimuli. Lindqvist (1959) of Helsinki also agrees with Seyffarth that progressive fatigue is accompanied by a decrease in the amplitude of motor unit potentials (fig. 44).
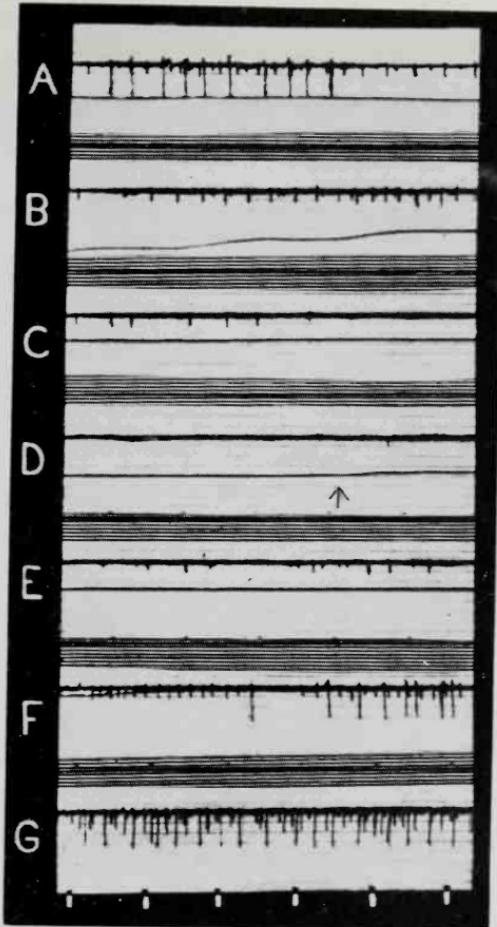
Fig. 42. Fatigue experiment. *A*, Single maximum contraction 30 minutes after the blood pressure cuff is inflated to obstruct circulation to forearm. The larger units have a slow frequency, though there is maximum effort. *B* to *G*, The subject is trying all the time (40 seconds) to maintain maximum load. *B*, ½ second after *A*. Though there is maximum effort, the contraction develops very slowly and is painful. Only the small unit is left. *C*, 10 seconds after *B*—the unit disappears in spite of the higher tension (produced by the muscles above the cuff). *D*, 18 seconds after the beginning of maximum contraction at *B*. Next, the cuff is relaxed. *E*, 9 seconds after *D*—the small unit appears. *F*, 13 seconds after *D*—the larger unit appears. *G*, 22 seconds after *D*—several units are present, but the frequency of the larger unit is slow (13 per second), though there is maximum effort. (From Seyffarth, 1940.)
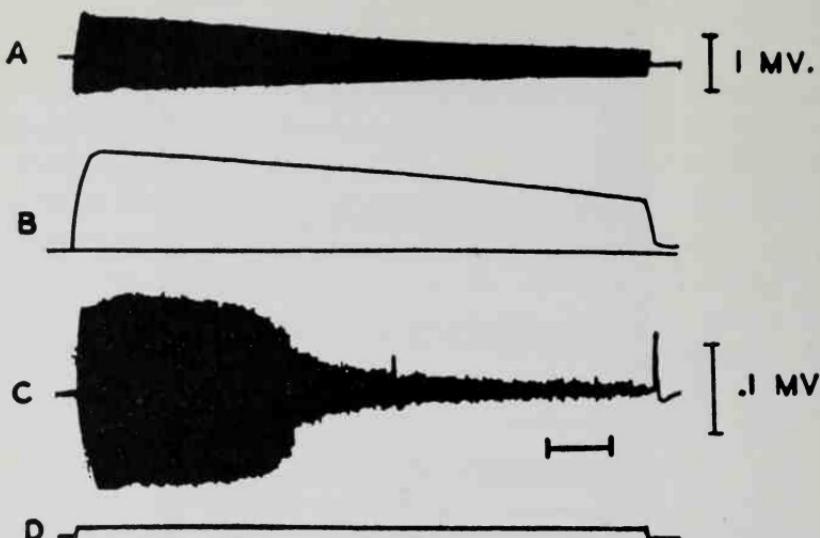
Fig. 43. Effects of fatigue in an isotonic contraction during indirect stimulation. Stimulus 4V, 38 per second. After-load, 20 g. Time axis, 2 seconds. A, EMG taken with bipolar needle electrode (tips 1 mm apart); D, stimulus signal. The amplitude of the "gross" EMG, A, closely parallels the contraction height, B. The sudden decline in amplitude of the electrical record of a small group of fibres, C, is interpreted as the result of the "dropping out" of a few fibres, whose loss is not apparent in the "gross" EMG. (From Loofbourrow, 1948.)

Lundervold (1951) found that after repeated contractions of hand muscles to the point of being "completely tired out," the accessory muscles involved showed no serious emg alteration. Indeed, more and more potentials were recruited. Muscles not considered essential to a particular movement were recruited and hyperactive (fig. 45). After resting the limb because of extreme subjective fatigue, tremors appeared.

In contrast, Merton (1954) has demonstrated a peripheral fatigue which appears not to be due to neuromuscular blocking. He showed that the blood supply is the significant factor even in contractions of a single small muscle. Even in extreme fatigue under the special experimental conditions used by Merton, action potentials evoked by motor nerve stimulation were not diminished
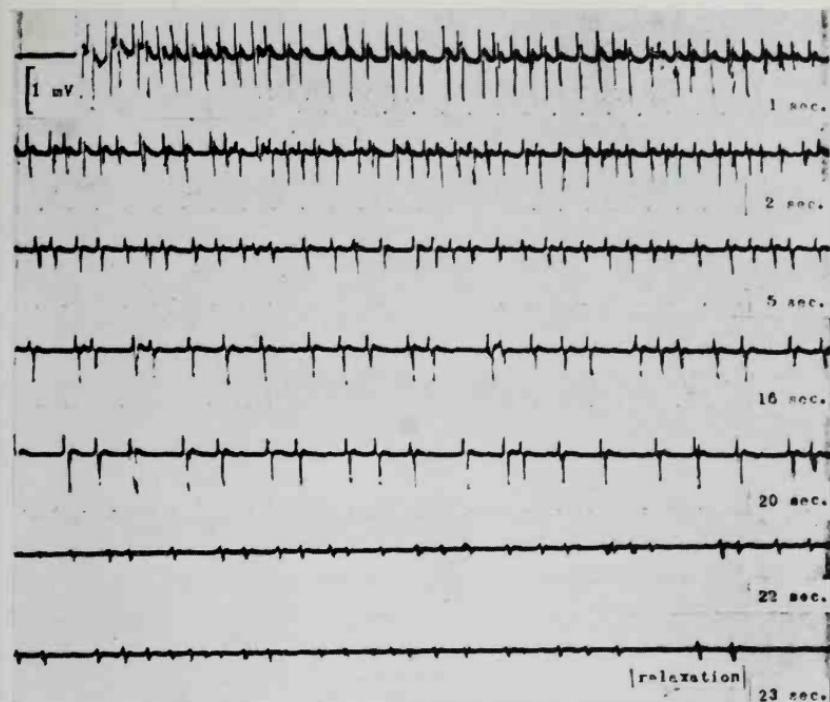
Fig. 44. Fatigue EMG. The train of single oscillations of a slightly irregular motor unit potential. The shape of the impulse is rather stable. The decrease of amplitude approaches the noise level. (Partly paralyzed extensor digitorum, bipolar needle electrode.) (From Lindqvist, 1959.)

(fig. 46). Recovery from this type of fatigue does not take place if the circulation is kept arrested, further underlining Merton's assertion.

Christensen (1962) hypothesizes that myohemoglobin plays a very important rôle in preventing fatigue from acute activity of brief duration. On the other hand, it is used up in longer exercise resulting in the symptoms, objective signs and positive tests that indicate fatigue. Repeated periods of great effort not exceeding $\frac{1}{2}$ minute with equal rest periods did not cause fatigue.

In the past few years our experience has shown that the fatigue experienced in heavily loaded upper limbs is not accompanied by any significant muscular activity. Yet "fatigue" becomes unbear-
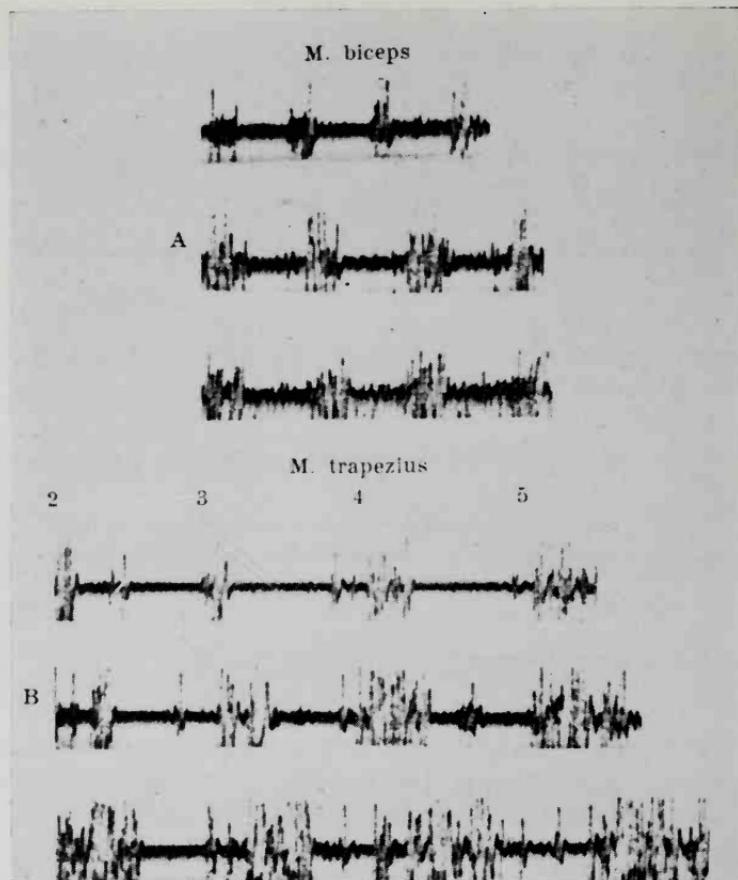
FIG. 45. Fatigue EMG recorded from needle-electrode. A, biceps brachii, while the subject is repeatedly striking a typewriter key with the right index finger at maximal speed. The curves are led off at intervals of 1 minute and four strokes are recorded each time. B, trapezius, while the subject is continuously striking the keys at maximal speed with the four fingers. The curves are recorded at intervals of 1 minute. (From Lundervold, 1951.)

able. This particular type is apparently due to the painful strain on the ligaments and capsules. This concept will be enlarged upon below under the heading "Muscles Spared When Ligaments Suffice" (p. 131).

During sustained contraction recorded with surface electrodes
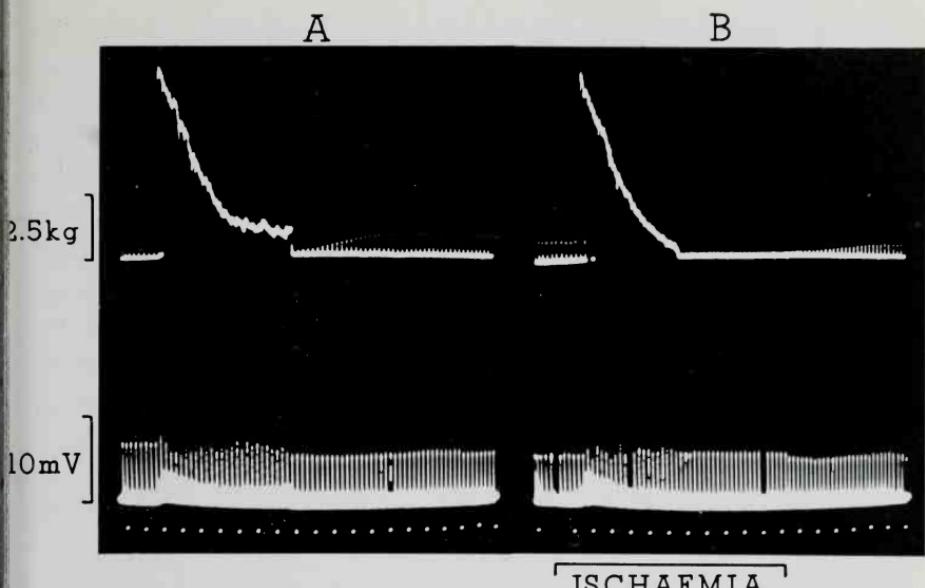
FIG. 46. Fatigue: mechanical myogram and EMG. *A*, maximal voluntary effort persisted in until severely fatigued. A series of single twitches (evoked by nerve shocks) precede and follow. *Lower tracing*, the corresponding emg action potentials. Time markers, ½ minute. *B*, the same but with the circulation occluded for the period indicated by a line (labelled ischaemia) beneath the record. (From Merton, 1954.)

over flexor digitorum superficialis in the forearm, Eason (1960) found that the amplitude of the integrated EMG increases progressively with time in both active and passive muscle. He suggested that additional motor units are progressively recruited to compensate for the loss in contractility due to impairment of fatigued units. The action potentials summate with those of already active units to more than offset the drop of amplitude of the impaired units. Eason also reported that surface EMG's progressively increased in amplitude with continuous or repeated contractions *not* associated with fatigue. The rate of increase was proportional to the magnitude of contraction.

Part of the findings of Missiuro, Kirschner and Kozlowski (1962a, b) of Warsaw were rather similar. Integrated EMG's from surface electrodes over biceps and triceps grow steadily during

intense physical exertion. The EMG in the final stage of exertion shows evidence of synchronization of potentials. Missiuro *et al.* suggest two mechanisms of fatigue during effort: one, peripheral, produced by intense exertion; and the other, central, occurring with prolonged low-intensity work. In the latter case, there are few emg signs of peripheral changes, i.e., even up to ultimate stages of fatigue when the subject consciously reduces his effort and therefore the output of potentials.

Zhukov and Zakharyants (1959) of Leningrad studied progressive fatigue in biceps and triceps put under continuous supporting activity against a load. At a certain stage of fatigue the supporting or lifting of the load appeared to be subjective. When the effort is maintained, typical changes appear in the EMG. The amplitude of potentials rises and the integrated level of voltage rises; synchronization of potentials appear, as reported also by Missiuro *et al.*

The Scottish physicians Lenman and Potter (1966) found the electrical changes associated with fatigue to be more prominent in patients with rheumatoid diseases and in the myopathic disorders. Yet the mean slope of the voltage-tension regression curves do not differ from that of healthy persons.

Studying the fatigue in rectus femoris of normal young men made to perform the Harvard step test, Sloan (1965) found little or no change in electrical activity in the absence of local fatigue. When more challenging exercise was imposed and fatigue occurred, the EMG amplitude increased with no consistent change in frequency. He could demonstrate no synchronization of potentials reported by others.

Using computerized methods of auto- and cross-correlation of potentials from different parts of one muscle during fatigue experiments, Person and Mishin (1964) confirmed beyond any doubt that synchronization of motor units *does* occur.

Sato, Hayami and Sato (1965) of Tokyo were particularly interested in the differences in the fatiguability of two-joint and one-joint muscles. They found little difference in EMG changes in two-joint and one-joint muscles that lie superficial. But during

fatigue the EMG spectra fell much more in the gastrocnemius then it did in soleus which lies deep to it. Deep one-joint muscles appear to be more difficult to fatigue than an overlying two-joint muscle.

Scherrer and his colleagues showed in a recent emg study (1957 *et seq.*) that different views of normal muscular fatigue result from experimenting with human subjects and with animals and, apparently, also with the type of experimental technique used. There is, they find, a difference between the fatigue of repeated maximal effort and that of continuous contraction. This is not to deny the findings of a number of groups, such as Poudrier and Knowlton (1964) who find that fatigue brought on by intense repetitive or sustained strong contraction is peripheral to the myoneural endplate.

Scherrer, Lefebvre and Bourguignon (1957) suggest that Merton's demonstration of a reduction in the mechanical response without a concomitant reduction in the electromyographic potentials during maximal contractions is quite different from their own finding of progressive change in the EMG with continued prolonged mechanical work. The potentials show increased amplitude and decreased frequency (Scherrer and Bourguignon, 1959).

Under the direction of Professors Monod and Scherrer, Phuon-Monich (1963) confirmed that there is an augmentation of electrical activity in muscle during fatigue caused by intermittent static work. The results were similar to those found with other forms of local work. Larsson, Linderholm and Ringqvist (1965) found that after intense sustained contractions and, to a lesser extent, after rhythmical contractions, polyphasic potentials increased in number. This was reversible. As in other studies, their action potentials decreased in duration but there was no change in amplitude.

In effect, the character of the electrical activity during voluntary exercise is a reflection of the EMG, or *vice versa*. Phenomena appear during the fatigue of prolonged work which are probably of spinal cord origin and still not well understood. Various authors have described various phenomena that occur with the progres-

sive fatigue of continuous activity. These include synchronization of potentials (Lippold *et al.*, 1957), the rhythm of Piper (1912), an augmentation of the amplitude and duration of potentials, and an increase in polyphasic potentials. The specially interested reader should see the two long papers of Scherrer *et al.* (1957, 1960) for an excellent review of the present opinions on these matters.

In conclusion, it must be stated that, upon the available evidence, direct fatigue of human muscle fibres *per se* under normal conditions is impossible and that the ordinary fatigue experienced by mortals is a much more complex phenomenon.

Control of Muscle Contraction

FEEDBACK. There is no doubt now that the state of contraction of a muscle is controlled by information "fed back" from it to the spinal cord centres. Such feedback loops have been the subject of considerable basic research. (See Granit, 1964, for a brief but clear review.) Lippold, Redfearn and Vučo (1957) showed that a periodicity or modulation appears in normal motor unit potentials (from 8 to 14 per second) which is related to tremor, but is not normally visible to the naked eye. This modulation, increased by stretching a muscle or by the fatigue of effort and decreased by cooling is due to oscillation in the stretch reflex "servo loop" (fig. 47). Perhaps the tremors of various disorders are an exaggeration of this physiological periodicity or rhythmical activity of groups of motor units.

Eble (1961) has shown electromyographically that the muscles of the back (in acute spinal-rabbit preparations) function reflexly in various antagonistic and synergistic pairs. He concluded that the normal rôle of reciprocal innervation is to modify the excitability levels of appropriate neurons rather than to diminish activity in antagonist muscles which is, as we shall see, normally nonexistent (p. 86).

TONIC NECK REFLEXES. For a discussion of reflex contraction in the neck which apparently increases the performance of upper limb movements see page 335.
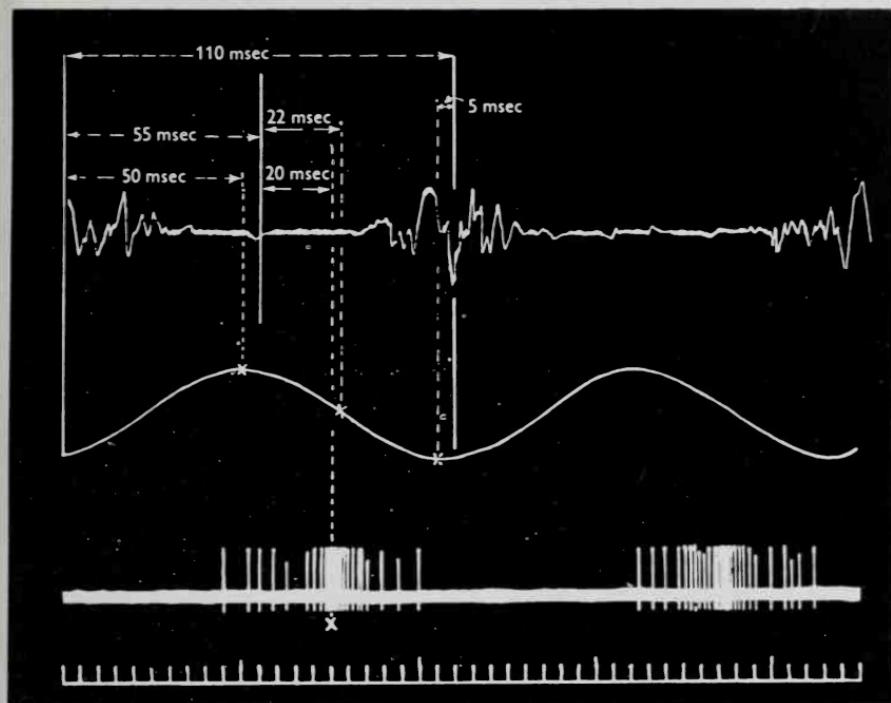
FIG. 47. Diagram of the relation (in human calf muscle) between electrical activity (*top*), mechanical record (*middle*) and spindle activity (whose time relations are calculated from a reflex time of 35 msec, which was the mean value of 10 determinations made during the same experiment). The action potential bursts are spaced at 110-msec intervals. The muscle is fully shortened at 50 msec later, which equals a phase lag of 170°. At the calculated time of greatest spindle discharge the velocity of lengthening of the muscle is at a maximum. Under these conditions, spindles therefore are sensitive to velocity (not tension or displacement). Displacement record shows an increase in muscle length as a downward deflexion. (From Lippold, Redfearn and Vučo, 1957.)

MUSCULAR RESPONSE TO PASSIVE STRETCH. Although Granit and his associates (1956, 1957, 1958) suggest that in mammals there exist both tonic and phasic motor units just like those in invertebrates, this concept has not been generally accepted. Becker (1960) has adduced electromyographic evidence that for the first

time strongly supports this view as being valid—at least in certain muscles in the normal human being. Passive stretch of the long head of triceps brachii and soleus muscles—but not the short head of triceps and gastrocnemius—produced peculiar motor unit potentials which were unlike voluntary motor unit potentials. These potentials Becker has analyzed and he concludes that they come from special tonic motor units responding only to stretch. This preliminary work shows promise, but requires confirmation.

Coordination, Antagonists and Synergy

One often sees the owlish statement that the brain does not order a muscle to contract but orders movements of a joint. As clever as it sounds, this statement is only true in part. Under certain circumstances the movement is, in fact, the result of contraction in only one or two muscles. This we have shown repeatedly by our various studies. For example, pronation of the forearm is usually produced by one muscle alone—pronator quadratus—unless added resistance is offered to the movement; then, more muscles are called upon (Basmajian and Travill, 1961). My colleagues and I have found this to be true in elbow-flexion too, where brachialis alone often suffices, and in other movements. Therefore, it is wrong and misleading to believe that nature always calls upon groups of muscles to produce simple movements. On the other hand, there are complex movements (such as rotation of the scapula on the chest wall during elevation of the limb) which obviously call upon groups of cooperating muscles (see p. 163).

Antagonists, too, have been misrepresented in the normal functioning of muscles. The unfortunate and incorrect impression has been fostered by many physiologists and even more anatomists that during the movement of a joint in one direction muscles that move it in the opposite direction show some sort of antagonism. The truth of the matter, first proposed by Sherrington as "reciprocal inhibition" is that the so-called antagonist relaxes completely (Travill and Basmajian, 1961) except perhaps with one exception—at the end of a whip-like motion of a hinge joint. Here,
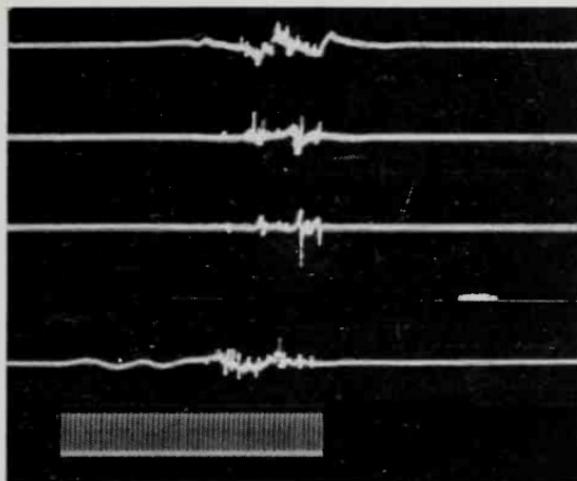
Fig. 48. EMG of elbow-flexors during rapid *extension* of elbow (0.1-msec time marker indicates duration). EMG tracings (*from above downwards*): biceps brachii long head; short head; brachialis; and brachioradialis. Burst of activity in the flexors at the end of extension.

apparently, the short sharp burst of activity in some antagonists occurs to prevent damage to the joint; this was first implied by Barnett and Harding (1955) and later supported by our own work (Basmajian, 1957, 1959) (see fig. 48) and that of Bierman and Ralston (1965). These investigators at the Biomechanics Laboratory of the University of California in San Francisco recorded the emg potentials in rectus femoris and biceps femoris while subjects had their knee moved passively and when they actively performed flexion and extension of the knee (fig. 49). When they turned their attention to what the antagonists are doing during active movements, they found that toward the end of such a movement, potentials occurred in the antagonist (fig. 49). They did not ascribe this to a stretch reflex as such, but they did consider the action as a regulatory one acting in proper timing through central feedback loops. They would agree that this brief terminal activity in antagonists serves a protective function to "avoid damage which such a force [in the prime mover] could produce."

The oft-used term *antagonist* should be replaced, in my opinion,
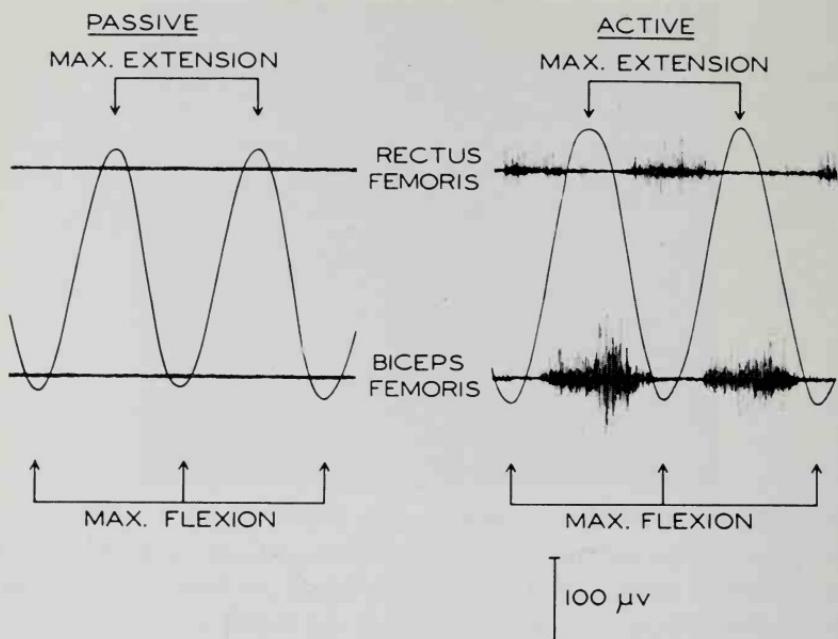
Fig. 49. EMG of rectus femoris and biceps femoris during passive and active flexion of the knee. (From Bierman and Ralston, 1965.)

by the companion word *synergist*. When "antagonists" act they really act just to prevent undesired movement, and their only important application as antagonists is in their acting against gravity. Because nervous coordination is so fine, there is no need for muscles to act in antagonism to others simultaneously. The rule, then, is for the "antagonist" to relax.

One finds that the activity of muscles in the position of antagonists during a movement is a sign of nervous abnormality (e.g., the spasticity of paraplegia) or, in the case of fine movements requiring training, a sign of ineptitude. Indeed, the athlete's continued drill to perfect a skilled movement exhibits a large element of progressively more successful repression of undesired contractions. O'Connell has demonstrated this convincingly in her unpublished emg studies at Boston University. A group of physical-education majors required to perform "head stands" while being studied electromyographically could be graded as to their actual

experience by the amount of overflow of undesired activity in muscles that were only casually related to the exercise. (See also section under "Training," p. 96.)

Hirschberg and Dacso (1953), on the other hand, would seem to disagree with my opinion. In an early emg study, they appeared to conclude that simultaneous activity of agonists and antagonists is a common phenomenon, but unconsciously they come closer to my own position with their almost parenthetical statement that such activity is seen in ". . . strenuous motion or in tense experimental subjects." Furthermore, Lundervold's extensive experiments (1951), referred to on page 78, appear also to contradict Hirschberg and Dacso. Miles, Mortensen and Sullivan (1947) in an early study stated that potentials could be recorded from topographical antagonists, but the circumstances of their experiments were somewhat too specialized to make so sweeping a generalization today.

Dempster and Finerty (1947) in an early emg study set out to determine the influence of varying gravitational effects on the large number of muscles that may cross one joint—specifically, the 15 muscles that cross the wrist held in a horizontal position. Furthermore, they were concerned with the influence of torques or moments of force at the pivot. Finally, they employed rather esoteric calculations (of no interest to the general reader) to explain their findings.

For static support, the torque at the wrist produced by gravity must be balanced neatly by the torque of those muscles which are in an advantageous position, i.e., crossing above the horizontal level of the wrist pivot. However, Dempster and Finerty found that synergists were active as well and these were obviously not in a position to exert an antigravity torque. This activity in the synergists or stabilizers was about half that in the antigravity or main group (which they referred to as "agonists"). Muscles that were below the wrist pivot and therefore in no position to act against gravity showed activity too; this was one quarter as much as that in the agonists, according to Dempster and Finerty. They then unfortunately dubbed these muscles "antagonists." If in-

deed any true activity of this nature occurs—and refined emg techniques seem to deny it—the activity is not a matter of antagonism to the agonists, for gravity does not require help. Rather it must be due to secondary synergic and postural functions of the muscles of the wrist and fingers.

By rotating the horizontally held wrist (supination and pronation) different groups of muscles were brought to a superior position. Here they assumed the burden of the gravity torque; others were placed in less advantageous positions in which, however, they continued activity as synergists, but with reduced intensity.

Using as a model the act of prehension of the hand, Livingston, Paillard, Tournay and Fessard (1951) of Paris demonstrated the plasticity of synergists during voluntary movements. Thus, the interplay of activity of the flexors of the fingers and of the thumb with those of the forearm was shown during normal activity to vary significantly depending on the information of peripheral origin, e.g., position of joints, angle at which the synergists act, the nature of objects grasped, etc. More recently, Weathersby (1966) reported that there is considerable synergistic activity in certain forearm flexors during ordinary movements of the thumb.

Missiuro and Kozlowski (1961) illustrated the ultimate plasticity of synergists. In a study of rabbit muscle transplanted to the place of its "antagonist," they found the transplant took on the function of the anatomical and functional "antagonist." Obviously the nervous system is able to adapt readily to such changes.

We know that many contractions of any one particular muscle may be accompanied by synergistic activity in other muscles to steady the adjacent joints. Gellhorn (1947) thus demonstrated the rôle of far-removed synergists in movements of the wrist. While flexor carpi radialis was activated in very slight flexion of the wrist, triceps brachii became active with the increasing effort in the prime movers (the extensors of the wrist remaining relaxed meanwhile). Only with very strong static flexion of the wrist would activity—and that only occasionally—appear in the antagonists.

Gellhorn found three stages of recruitment of synergists, depending on the stress. In the first, the activity is confined to the agonist at the wrist. In the second, action potentials appear in the agonist and a muscle of the upper arm according to the following rule: biceps muscle becomes active with flexion of the supine wrist and with extension of the prone wrist, whereas the triceps becomes active with the reverse conditions (i.e., extension of the supine and flexion of the prone wrist). In the third stage, with excessive straining, some activity appears in antagonists as well but it is never equal to the activity of the prime mover and of the synergists. The exact significance of Gellhorn's patterns of recruitment are obscure but may be of fundamental importance. In any case, they stress the concept that "antagonists" are really only synergists.

Along the same line, experiments were done by Sills and Olsen (1958) in the hope of demonstrating activity in the unexercised arm while the opposite arm was exercised by normal subjects. There was, in these normal persons, little if any such "spread" to the opposite limb musculature unless extremely powerful movements were made. (See also our similar findings, p. 221 and the section below under "Effects of Cross Exercise.") Their conclusions effectively demolish the basis for certain contralateral exercises that have been advocated for developing muscles, especially for an injured limb too painful or too immobilized to be moved itself.

Recent electromyographic studies of abnormalities in the plantar reflex response have fallen neatly into this general concept, too. The "up-going toe" of upper motor neuron lesions has been found by Landau and Clare (1959) to be the result of an exuberant overflow of activity to the great toe extensors; even though the flexors continue to contract, the extensors overpower them (fig. 50).

In the very young normal child and especially premature babies, the same sort of phenomenon was demonstrated by Fényes, Gergely and Tóth (1960) with "flexion reflexes" observed electromyographically. Both agonists and antagonists contract in
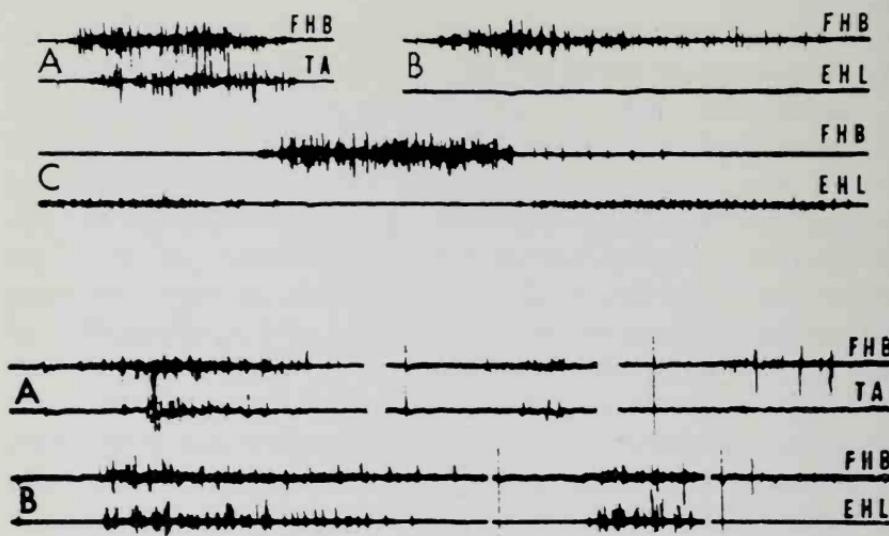
FIG. 50. Normal flexor response (*upper set of traces*) compared with the abnormal extensor response (*lower set*). EMG's from flexor hallucis brevis and extensor hallucis longus. (Composite of segments of two illustrations from Landau and Clare, 1959.)

what they term a "co-reflex phenomenon." The same is true in spastic children with cerebral palsy during locomotion (Kenney and Heaberlin, 1962). There is an abrupt onset of the agonists and a rapid response of the antagonists with sufficient power to be obstructive. Under considerable resistance, normal children give the same response of exuberant (but wasteful or useless) over-activity of antagonists.

Rao (1965) has shown by EMG that, contrary to general opinion, reciprocal inhibition does not occur with the ankle jerk reflex. But he confirms its validity when voluntary actions are performed. Motor units in tibialis anterior act as briskly as those in gastrocnemius when the tendon of Achilles is tapped. He explains this reversal of normal inhibition in the "antagonist" as part of the positive supporting reaction in which the principle of reciprocal innervation is not applicable.

In a study of reflex reactivity of biceps and triceps in children at different developmental stages, the Polish investigator, Missiuro (1963), found a spread of electrical activity to other muscles

of the same extremity. With increasing age this decreases so that in adult life it is minimal.

Vladimir Janda (1966, personal communication) of Prague has shown a significant linkage of emg activity in certain separate muscle groups, especially in children. During a strong effort in a particular muscle, he finds a high incidence of activity (in a predictable pattern) in far removed muscles of the same limb and trunk musculature. Hellebrandt and her colleagues have convincingly drawn our attention to a patterned spread of gross muscular activity to wider and wider areas during forceful effort or exercise stress (Hellebrandt and Waterland, 1962a, b; Waterland and Hellebrandt, 1964; Waterland and Munson, 1964a, b).

In insects, simultaneous emg activity in antagonist muscles has been reported (Hoyle, 1964, in grasshoppers; Wilson, 1965, in cockroaches and locusts). These have no simple relationship and probably do not bear on the problem of synergy in mammals. The only possible connection is in the findings of Stuart, Eldred, Hemingway and Kawamura (1963) who showed that in shivering there are synchronous contractions in antagonistic muscles of mammals.

Effects of Cross Exercise

The hypothesis that there is a transfer of activity to the contralateral limb during prescribed exercise on one side has been frequently postulated, but now it is being seriously questioned. Probably it is invalid except in very special circumstances. Gregg, Mastellone and Gersten (1957) of Denver, Colorado, found that overflow to the unexercised, contralateral muscles did not occur during simple non-resistive exercises or during isometric contractions of one biceps brachii. As the exercise stress increased, however, there was some "overflow" to the opposite triceps and, after even greater stress, to the biceps. Increasing fatigue played an important rôle in the "overflow" but was reversible, for after a rest of two minutes "overflow" would at first be absent.

Samilson and Morris (1964) confirm the finding that in normal man activity of one upper limb is not accompanied by activity in the contralateral resting limb. However, in spastic children, there is such a spread. On the other hand Podivinský (1964) of

Bratislava, Czechoslovakia finds a slight motor irradiation occurs from the strong contraction of finger flexors to the related muscles of the opposite limb ("crossed motor irradiation"). This perhaps is related to the findings of Hellebrandt and her colleagues regarding indirect learning, i.e., the improvement of strength in one limb by exercising the opposite limb (Hellebrandt and Waterland, 1962a, b). Its practical significance in ordinary life is unknown and appears to have been exaggerated since the days of Scripture *et al.* (1894). We have shown that at the finest levels of control in motor unit training the role of cross-training is not significant (Basmajian and Simard, 1966).

Further, the crossed reflex phenomenon described by Ikai (1956) of Tokyo is not really the same phenomenon as cross exercise. Ikai showed that the crossed reflex of limbs in spinal animals can be reproduced under certain conditions as a brief overflow of monosynaptic reflexes to the opposite limb.

Panin, Lindenauer, Weiss and Ebel (1961) seem to have delivered a serious blow to the concept of "cross exercise." In their extensive study they found that the spread of activity was minimal to insignificant. Insignificant potentials of low amplitude and frequency appeared in all non-exercised muscles in a widespread distribution in all four limbs. They appeared most in areas required for postural stabilization of the subject's body. Even then the amount of activity was so slight as not to constitute exercise effect.

Our own studies on quadriceps (p. 139) and those of Sills and Olsen (see above) largely confirm the conclusions of Gregg and his colleagues. We found in our studies of spastic patients (p. 72), however, that an exuberant overflow occurs to the opposite limb. Walshe (1923) has written about a similar phenomenon in hemiplegia. We must conclude that "cross education" is, at best, of dubious value in *normal* subjects.

Spontaneous Muscle Cramps

Muscles in cramp have been studied electromyographically with needle electrodes and modern equipment by Denny-Brown and his colleagues (1948) and by Norris, Gasteiger and Chatfield

(1957). Such cramps occur rather frequently in apparently normal people as localized, involuntary, sustained contractions, which are sudden and very painful. They occur in the calves of swimmers (particularly early in the swimming season) and during sleep ("night cramps") particularly in pregnant women. Perhaps they are related to the cramps that occur as a symptom of a variety of diseases, but this has been contested.

Norris *et al.* (1957) studied cramps in a series of subjects in whom they were produced by an ingenious technique which grew out of their observations. Cramps could be brought on by getting "normal," cramp-prone youths to make a voluntary effort while a large muscle under study (e.g., the biceps brachii) was in a shortened position. The action potentials that they recorded through fine indwelling wire electrodes were those of normal motor units and therefore were initiated by motor impulses from the central nervous system. Reflexes and other superimposed manoeuvres altered and even initiated the cramps, thus supporting their conclusions.

Disuse Atrophy

Although in an early report Buchthal and Clemmesen (1941) gave a substantial account of emg changes in atrophy including disuse atrophy, no extensive literature exists on this variant of normal EMG. Fudema, Fizzell and Nelson (1961) studied the question using external fixation apparatus on the hind limb of cats. They found a continuing decrease of electrical output from tibialis anterior through the period of immobilization. This reflected the reduction in size of the muscle and, apparently, the muscle-fibre membrane area. No spontaneous fibrillation potentials occurred and the shape of motor units remained normal, indicating that the myoneural junction is not implicated in disuse atrophy.

Effects of Overheating and Cooling

Edelwejn (1964) found in a series of experiments on rabbits subjected to overheating that there is a statistically significant increase in polyphasic potentials (from 11% to 31%) and shorten-

ing of time of single polyphasic potentials. These fell from 9.5 msec at 37°C to 7.1 msec at 41°C. No changes were found in amplitude. Edelwejn proposes that the cause is due to changes in impulse transmission in the muscle fibres with some unexplained disturbance of integration in the muscle fibres of the motor unit.

Under controlled hypothermia, Serra, Pasanisi and Natale (1963) have found a progressive fall of 50 microvolts in mean amplitude and 0.5 msec in duration of potentials during ordinary contractions. Similar findings were obtained when electrically stimulated contractions were studied.

Effects of Smoking

Serra and Lambiase (1957) of Naples have demonstrated that cigarette smoking causes changes in the action potentials. There is a decrease in the frequency of single motor unit potentials at maximum effort with spontaneous monophasic and diphasic spikes appearing in apparently relaxed muscles. On voluntary activity there are changes in the shape of the potentials, many becoming polyphasic. Serra and Lambiase suggest that these changes result from a light carbon monoxide poisoning plus nicotinic effect at the myoneural junction and on the muscle fibre itself.

Rao and Rindani (1962) and Rao (1963) have also studied the effect of smoking on the EMG. In the second study, Rao found a delayed second spike appeared in the composite wave from muscles stimulated electrically through their motor nerves. He ascribes this second spike to the effect of nicotine on some of the neuromuscular junctions but also admits that the cause may be primarily in the muscle fibres themselves.

Training

Professor Mitolo of the University of Bari in Italy has shown (1956, 1957) that progressive physical training of a specific muscle produces a gradual increase in the average duration of its potentials (with a progressive diminution of their average frequency) and a gradual "regularization" of the response. This last might be expected to be a function of training in athletics, i.e., with

advanced training there is greater and greater efficiency and specificity of response.

The Russian physiologist, Person (1958), studied the electrical activity of the biceps and triceps brachii while subjects were trained in certain types of work (e.g., chopping and filing). Before the training, the rhythmical flexion and extension of the elbow were effected by exuberant, apparently wasteful, activity of the antagonist which is overcome by the greater activity of the agonist. With training, there is a progressive inhibition of the antagonist during the movements of flexion and extension until, with advanced training, the inhibition becomes complete. O'Connell's work, referred to on p. 88, agrees.

Proprioceptive Effects

Gellhorn (1960) has described electromyographic studies which disclose the effects of central proprioceptive influences on movements elicited by the electrical stimulation of the motor cortex. Movements so produced are strongly reinforced by proprioceptive impulses which also determine, by and large, the type of movement that results. He showed, for example, that the contraction of triceps and flexor carpi muscles when stimulated through the cerebral cortex is greater if the elbow is at $45°$ than if it is at $110°$ or $160°$. Furthermore, a cortical stimulus that is below threshold when a muscle is slack may become effective when the muscle is put on the stretch.

Electromyography of the Fetus and Newborn

Until recently, no reliable information was available in regard to the earliest muscle potentials during fetal development. The characteristics of the earliest potentials are of great interest both in embryology and in the related fields of electromyography and neurology. Particularly important is the relationship of the time of innervation to the time of appearance of the earliest potentials. Our laboratory therefore has been attempting to solve the problem and so we developed special techniques with which to examine a series of living vertebrate fetuses.
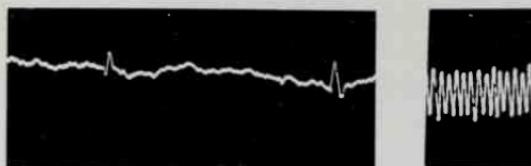
Fig. 51. Two emg potentials from shoulder region of a 17-day-old rabbit fetus (proved not to be ECG). Calibration (*at right*), 100 μv and 10 msec, peak to peak. (Ranney and Basmajian, 1960.)

The details of our methods and the detailed results have been published (Lewis and Basmajian, 1959, Ranney and Basmajian, 1960). A large number of rabbit fetuses and a limited number of goat fetuses have been studied.

In the rabbits (which have a gestation period of 32 days) all fetuses aged 18 days or more showed electromyographic potentials. At 17 days, only some of the fetuses had emg activity. This is the earliest fetal age in which we first observed visible movements. At 16 days, only one of 16 fetuses exhibited true muscle potentials. None of the younger fetuses did so.

The emg potentials of these fetuses ranged from as low as 13 μv to as high as 250 μv (fig. 51). Their durations were too long to classify them with the short-duration, small potentials which are known as fibrillation potentials and are diagnostic of denervation in post-natal life. Therefore, it has not been possible to state that the potential we found indicated a lack of innervation of the fetal muscles.

A few authors have described early visible movements in mammalian fetuses and embryos but these have not been intrinsic or spontaneous; rather, they have been in response to prodding or electrical stimulation. Straus and Weddell (1940) found contractions of the forelimb in fetal rats stimulated electrically in the latter half of the 15th day (of a 21-day gestational period). This is in general agreement with the finding of Windle *et al.* (1935). Windle (1940), furthermore, states that the site of earliest activity is in the lower cervical region; it was nearby, in the shoulder region, that we picked up our earliest muscle potentials. Appar-

ently, the onset of spontaneous activity requires a further degree
of maturation beyond the stage at which muscles respond to an
external stimulus.

Marinacci (1959), in a report on the EMG of prematurely born
infants, concluded that at the sixth month of intra-uterine life
(relatively much older than our rabbit fetuses) about 20% of the
muscle fibres have still to be innervated. At the time of birth, 5%
apparently have not yet received their nerve supply. At the end
of the fourth post-natal month, practically all the muscle fibres
have been innervated. The delayed innervation is largely in the
lower extremities, especially in the intrinsic muscles of the feet.

Prior to innervation, primitive muscle fibres theoretically
should possess an inherent tendency to spontaneous fibrillation
and related electrical activity. Marinacci found that muscle fibres
do fibrillate in premature infants corresponding to a stage in intra-
uterine life when, he believes, they might not all be innervated.
Our own extended studies of fetuses in goats and rabbits (Ranney
and Basmajian, 1960) failed to reveal any of the signs of spon-
taneous pre-innervation potentials. Botelho and Steinberg
(1965) confirmed this in the canine fetus. We can offer no real
explanation for this discrepancy; perhaps Marinacci's finding of
spontaneous fibrillation potentials in premature infants does not
necessarily prove their existence in normal fetuses *in utero*. Finally,
there may be a species difference. In fetal sheep, Änggård and
Ottoson (1963) found that skeletal muscles could be made to con-
tract at the 50th day, considerably before the time at which
myelination (and therefore normal functioning) of the axons
occurs.

During pre-natal development the fetal sheep shows marked
changes in neuromuscular function as studied by motor nerve
stimulation. Änggård and Ottoson found marked changes from
the early stage (50th day) to more advanced stages when spon-
taneous movements are common (100th day). Though not strictly
an emg study, this work bears upon our present concern. It clearly
indicates that, in mammalian embryos, speed of conduction of
motor axons is related to the amount of progressive myelination.

However, the excitable properties of the axons is independent. A key factor in neuromuscular function is the clear establishment of motor endings on the muscle fibres. In fetal sheep this occurs after about 50 days.

In normal newborn babies, Schulte and Schwenzel (1965) of Göttengen found irregular spontaneous bursts of normal motor unit activity in upper and lower limb muscles. These were sometimes reciprocal and sometimes strictly alternating between antagonistic muscles. In the upper limb the flexors were preferred. With hypertonic newborns, there was often constant tonic activity in certain muscle groups. This was widespread in the more severe cases.

EMG in Normal Fishes, Reptiles and Birds

Biologists have taken a new interest in the possibilities of using EMG for studying neuromuscular functions in intact vertebrates other than mammals. This is not the place for an exhaustive review of what has been accomplished. However, a few interesting illustrations are called for.

Ballintijn and Hughes (1965a, b) have investigated the muscular basis of the respiratory pumps in the trout and the dogfish. In brief, they find that the muscles of the mouth and gills of the trout may be divided into two main groups according to whether they are active or passive during the expansion or contraction phase of the pumps. The protractor hyoideus (geniohyoideus) is active only during the contraction phase. Moreover, there are differences depending on the depth of ventilation. Shallow ventilation is maintained by one group while deeper ventilation calls upon another group. Only during strong ventilation does the dilator operculi play a rôle in abduction of the gills.

Ballintijn and Hughes showed that there are variations in the pattern in different individuals and in the same individual at different times. They also find that the pattern in dogfish is different from that in the trout. In dogfish, electrical activity takes place almost synchronously among all the muscles when the two cavities through which water is passed are decreasing in volume.

During normal resting ventilation no electrical activity was recorded in the hypobranchial muscles. They became active during hyperventilation and when biting. During swimming of certain sharks, the whole branchial region remains in a relaxed condition and water enters the mouth. The amount is regulated by the adductor mandibulae (Ballintijn and Hughes, 1965b).

Other emg work on fish is now in progress in Leiden, Netherlands by J. W. M. Osse (personal communication) with the European perch. In Buffalo, N. Y., Carl Gans is studying the locomotor pattern of snakes. Fowl have been studied fairly extensively because of the occurrence of hereditary muscular dystrophy in chickens. One can expect a widespread increase in the use of EMG among biologists. With the marvellous improvement and practicality now available in telemetering devices, biologists have been provided with an excellent tool for dynamic studies of normal function.

Electromyography of Insects

Beránek and Novotný (1959), of Prague, Czechoslovakia, have recorded EMG's from the limb muscles of cockroaches. The records of voluntary movements reproduced in their paper resemble closely the complex interference pattern of the mammalian electromyogram except that the duration of individual spikes is somewhat shorter. Single motor unit potentials appear to consist of a slightly more complex wave-form. According to Beránek and Novotný, there is an isolated rhythmical discharge of such single motor units during "absolute motor rest" for long periods of time; this, of course, suggests that the insect does not relax completely at rest. [These workers also went on to demonstrate in denervated muscles of the insect spontaneous potentials which do not resemble fibrillation potentials in denervated mammalian muscles. Since a discussion of denervation is not called for here, specially interested readers should consult the original paper, which is in English.]

In Denmark, Eric Gettrup (1966) is studying the integrative processes within the pterothoracic ganglia of locusts, using records

of sensory and motor events. Variation of wing twisting during flight is controlled by motor unit activity that is influenced by impulses from sensilla found on both hindwing and forewing. One would hope that greatly increasing and widespread use will be made of such techniques for the study of the muscular activity involved in flying, hopping and walking in many different species of insects.

Conscious Control and Training of Motor Units and Motor Neurons

S TUDIES of neuromuscular and spinal-cord function have been growing increasingly complex in recent years without offering clearer answers to many fundamental problems. Especially confusing and fragmentary are theories on the influence of various cortical and subcortical areas on spinal motor neurons and motor units in man. It is therefore refreshing to be able to use and advocate a technique that not only proves to be quite simple but also promises to reveal considerable fundamental information. Ironically, the technique is only a modification of ordinary electromyography. This modification consists of regarding electromyographic potentials not for their own intrinsic value but as the direct mirroring of the activity of spinal motor neurons. Thus the group of muscle fibres in a motor unit is considered only as a convenient transducer that reveals the function of the nerve cell.

Perhaps the ultimate irony is that in their classic paper establishing the modern era of electromyography in 1929, Adrian and

Bronk suggested that ". . . The electrical responses in the individual muscle fibres should give just as accurate a measure of the nerve fibre frequency as the record made from the nerve itself." Even earlier, Gasser and Newcomer (1921) had shown that "the electromyogram is a fairly accurate copy of the electroneurogram." Perhaps as a reflection of the general turning away from man as an experimental animal in favour of more exotic beasts and preparations, no real use of these early conclusions has been made until recently. In fact, the implications in Gasser and Newcomer's work did not lead to any systematic use of electromyography for studying the behaviour of individual spinal motor neurons in any species even though the action potential of a motor unit picked up by direct electromyography reflects the activity of its spinal motor neuron.

No great progress was made until 1928-29 when Adrian and Bronk published two classic papers on the impulses in single fibres of motor nerves in experimental animals and man. Their method consisted of cutting through all but one of the active fibres of various nerves and recording the action currents from that one fibre. They also succeeded in making records directly from the muscles supplied by such nerves. Somewhat incidentally, Adrian and Bronk introduced the use of concentric needle electrodes with which the activity of muscle fibres in normal human muscles could be recorded. Meanwhile Sherrington (1929) and his colleagues had crystallized their definition of a motor unit as "an individual motor nerve together with the bunch of muscle-fibres it activates." (Universally, later workers have also included in their definition the cell body of the neuron from which the nerve fibre arises.)

Although in subsequent years the concentric needle electrode was seized upon for extensive use, until the Second World War only a handful of papers appeared on the characteristics of action potentials from single motor units in voluntary contraction. In 1934, Olive Smith reported her observations on individual motor unit potentials, their general behaviour and their frequencies. She showed that normally there is no proper or inherent rhythm

acting as a limiting factor in the activity of muscle fibres; rather, the muscle fibres in a normal motor unit simply respond to each impulse they receive. Confirming earlier work of Denny-Brown (1929) she set at rest the false hypothesis of Forbes (1922) that the muscle fibres or motor units were fatiguable at the frequencies they were called upon to reproduce by their nerve impulses.

Forbes had also suggested that normal sustained contraction requires rotation of activity among quickly fatiguing muscle fibres. Smith proved that such a rotation need not occur and that an increase in contraction of a whole muscle involves both increase in frequency of impulses in the individual unit and an accession of new units which are independent in their rhythms. The frequencies ranged from 5 to 7 per second to 19 to 20 per second, although "highly irregular discharge may occur at threshold both during the onset of a contraction and during the last part of relaxation." Finally, she proved that tonic contraction of motor units in normal mammalian skeletal muscle fibre, the existence of which was widely debated, does not exist. Two generations later, there are people in muscle research still not aware of her definitive studies.

Lindsley (1935), working in the same physiology laboratory as Smith, determined the ultimate range of motor unit frequencies during normal voluntary contractions. Although others must have been aware of the phenomenon, he seems to have been the first to emphasize that at rest "subjects can relax a muscle so completely that . . . no active units are found. Relaxation sometimes requires conscious effort and in some cases special training."

In none of his subjects was "the complete relaxation of a muscle difficult." Since then, this finding has been confirmed and refined by hundreds of investigators, using much more sophisticated apparatus and techniques than those available in the early 30's.

Lindsley also reported that individual motor units usually began to respond regularly at frequencies of 5 to 10 per second during the weakest voluntary contractions possible and some could be fired as slow as 3 per second. The upper limit of frequencies was usually about 20 to 30 per second but occasionally

was as high as 50 per second. Earlier, Adrian and Bronk (1928, 1929) had found the same upper limit of about 50 per second for the nerve impulses in single fibres of the phrenic nerve and from the diaphragm of the same preparations.

Gilson and Mills (1940, 1941), recording from single motor units under voluntary control, reported that discrete, slight and brief voluntary efforts may call upon only a single potential (i.e., a single twitch) of a motor unit being recorded. Twenty years later, Harrison and Mortensen (1962) showed that by means of surface and needle electrodes action potentials of single motor units could be identified and followed during slight voluntary contractions in tibialis anterior. Subjects provided with auditory and visual cues could produce "single, double and quadruple contractions of single motor units . . ." and in one case, ". . . the subject was able to demonstrate predetermined patterns of contraction in four of the six isolated motor units."

Using special indwelling fine-wire electrodes (p. 32), I had no difficulty in confirming these findings (Basmajian, 1963), and on this basis I was able to elaborate techniques for studying the fine control of the spinal motor neurons, especially their training, and the effects of volition. Later, my colleagues and I further developed and described our system of testing and of motor unit training. We demonstrated the existence of a very fine conscious control of pathways to single spinal motor neurons (Basmajian, Baeza and Fabrigar, 1965). Not only can human subjects fire single neurons with no overflow (or perhaps more correctly, with an active suppression or inhibition of neighbours), but they can also produce deliberate changes in the rate of firing. Most persons can do this if they are provided with aural (and visual) cues from their muscles.

Following the implantation of fine-wire electrodes and routine testing, a subject needs only to be given general instructions. He is asked to make contractions of the muscle under study while listening to and seeing the motor unit potentials on the monitors (fig. 52). A period of up to 15 minutes is sufficient to familiarize him with the response of the apparatus to a range of movements and postures.
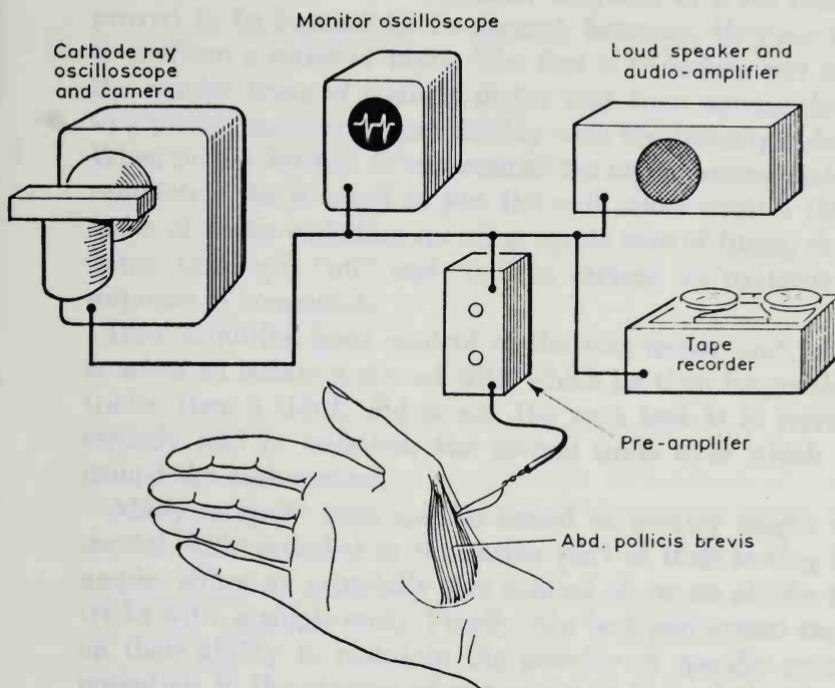
FIG. 52. Diagram of arrangement of monitors and recording apparatus for motor unit training. (From Basmajian, 1963b.)

Subjects are invariably amazed at the responsiveness of the loudspeaker and cathode-ray tube to their slightest efforts, and they accept these as a new form of "proprioception" without difficulty. It is not necessary for subjects to have any knowledge of electromyography. After getting a general explanation they need only to concentrate their attention on the obvious response of the electromyograph. With encouragement and guidance, even the most naive subject is soon able to maintain various levels of activity in a muscle on the sensory basis provided by the monitors. Indeed, most of the procedures he carries out involve such gentle contractions that his only awareness of them is through the apparatus. Following a period of orientation, the subject can be put through a series of tests for many hours.

Several basic tests are employed. Since people show a consider-

Fig. 42 Diagram of arrangement of monitors and recording apparatus for motor unit training. (From Basmajian, 1963.)

able difference in their responses, adoption of a set routine has proved to be impossible. In general, however, they are required to perform a series of tasks. The first is to isolate and maintain the regular firing of a single motor unit from among the 100 or so a person can recruit and display with the technique described. When he has learned to suppress all the neighbouring motor units completely, he is asked to put the unit under control through a series of tricks including speeding up its rate of firing, slowing it down, turning it "off" and "on" in various set patterns and in response to commands.

After acquiring good control of the first motor unit, a subject is asked to isolate a second with which he then learns the same tricks; then a third, and so on. His next task is to recruit, unerringly and in isolation, the several units over which he has gained the best control.

Many subjects then can be tested at greater length on any special skills revealed in the earlier part of their testing (for example, either an especially fine control of, or an ability to play tricks with, a single unit). Finally, the best performers are tested on their ability to maintain the activity of specific motor-unit potentials in the absence of either one or both of the visual and auditory feedbacks. That is, the monitors are turned off and the subject must try to maintain or recall a well-learned unit without the artificial "proprioception" provided earlier.

Any skeletal muscle may be selected. The ones we have used most often are the abductor pollicis brevis, tibialis anterior, biceps brachii and the extensors of the forearm.

Ability to Isolate Motor Units

Almost all subjects are able to produce well-isolated contractions of at least one motor unit, turning it off and on without any interference from neighbouring units. Only a few people fail completely to perform this basic trick. Analysis of poor and very poor performers reveals no common characteristic that separates them from better performers.

Most people are able to isolate and master one or two units
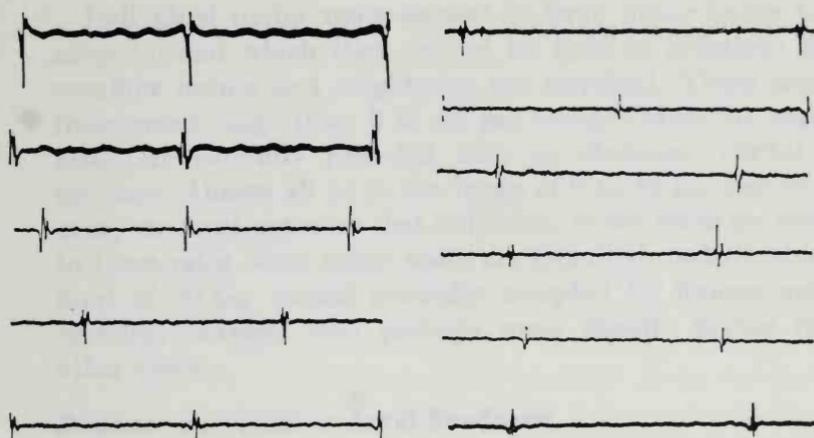
FIG. 53. Eleven different motor units isolated by a subject in quick succession in his abductor pollicis brevis. (From Basmajian, Baeza and Fabrigar, 1965.)

readily; some can isolate and master three units, four units and even six units or more (fig. 53). This last level of control is of the highest order, for the subject must be able to give an instant response to an order to produce contractions of a specified unit without interfering activity of neighbours; he also must be able to turn the unit "off" and "on" at will.

Control of Firing-Rates and Special Rhythms

Once a person has gained control of a spinal motor neuron, it is possible for him to learn to vary its rate of firing. This rate can be deliberately changed in immediate response to a command. The lowest limit of the range of frequencies is zero, i.e., one can start from neuromuscular silence and then give single isolated contractions at regular rates as low as one per second and at increasingly faster rates. When the more able subjects are asked to produce special repetitive rhythms and imitations of drum beats, almost all are successful (some strikingly so) in producing subtle shades and coloring of internal rhythms. When tape-recorded and replayed, these rhythms provide striking proof of the fineness of the control.

Individual motor units appear to have upper limits to their rates beyond which they cannot be fired in isolation; that is, overflow occurs and neighbours are recruited. These maximum frequencies range from 9 to 25 per second (when the maximum rates are carefully recorded with an electronic digital spike-counter). Almost all lie in the range of 9 to 16 per second. However, one must not infer that individual motor units are restricted to these rates when many units are recruited. Indeed, the upper limit of 50 per second generally accepted for human muscle is probably correct, with perhaps some slightly higher rates in other species.

Reliance on Visual or Aural Feedback

Some persons can be trained to gain control of isolated motor units to a level where, with both visual and aural cues shut off, they can recall any one of three favorite units on command and in any sequence. They can keep such units firing without any conscious awareness other than the assurance (after the fact) that they have succeeded. In spite of considerable introspection, they cannot explain their success except to state they "thought about" a motor unit as they had seen and heard it previously. This type of training probably underlies ordinary motor skills.

Variables Which Might Affect Performance

We find no personal characteristics that reveal reasons for the quality of performance (Basmajian, Baeza and Fabrigar, 1965). The best performers are found at different ages, among both sexes, and among both the manually skilled and unskilled, the educated and uneducated, and the bright and the dull personalities. Some "nervous" persons do not perform well—but neither do some very calm persons.

Carlsöö and Edfeldt (1963) also investigated the voluntary control over individual motor units. They concluded that: "Proprioception can be assisted greatly by exeroceptive auxiliary stimuli in achieving motor precision." Nevertheless, Wagman, Pierce and Burger (1965), using both our technique and a tech-

nique of recording devised by Pierce and Wagman (1964), emphasize the rôle of proprioception. They stress their finding that subjects believe that certain positions of a joint must be either held or imagined for success in activating desired motor units in isolation.

We have recently completed an investigation into various factors which affect motor unit training and control (Simard and Basmajian, 1967; Basmajian and Simard, 1966; Simard, Basmajian and Janda, 1967). We find that moving a neighbouring joint while a motor unit is firing is a distracting influence but most subjects can keep right on doing it in spite of the distraction. We tend to agree with Wagman and his colleagues who believe that subjects require our form of motor unit training before they can fire isolated specific motor units with the limb or joints in varying positions. Their subjects reported that "activation depended on recall of the original position and contraction effort necessary for activation." This apparently is a form of proprioceptive memory and almost certainly is integrated in the spinal cord.

Our observations were based on trained units in the tibialis anterior of 32 young adults. They showed that motor unit activity under conscious control can be easily maintained despite the distraction produced by voluntary movements elsewhere in the body (head and neck, upper limbs and contralateral limb). The control of isolation and the control of the easiest and fastest frequencies of discharge of a single motor unit were not affected by those movements (fig. 54).

Turning to the effect of movements of the same limb, we found that in some persons a motor unit can be trained to remain active in isolation at different positions of a "proximal" (i.e., hip or knee), "crossed" (ankle), and "distal" joints of a limb (fig. 55). This is a step beyond Wagman, Pierce and Burger (1965) who observed that a small change in position brings different motor units into action. Consequently they noted the important influence of the sense of position on the motor response. The present investigation shows that in order to maintain or
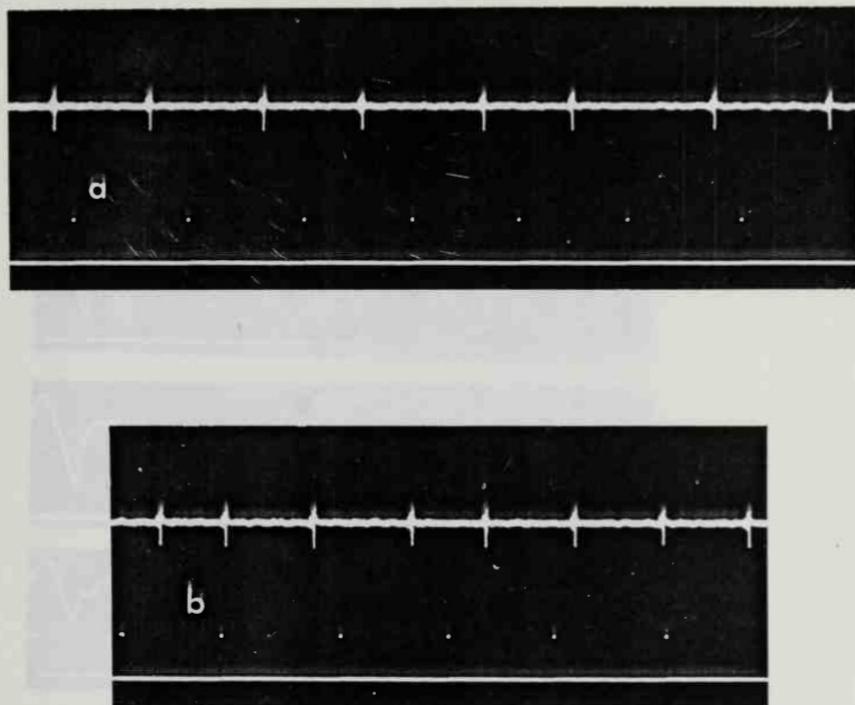
Fig. 54. Sample EMG of (*a*) the easiest, and (*b*) the fastest frequency of discharge of a motor unit in the right tibialis anterior during movements of the contralateral limb (time mark: 10-msec intervals). (From Basmajian and Simard, 1966.)

recall a motor unit at different positions, the subject must keep the motor unit active during the performance of the movements; and, therefore, preliminary training is undeniably necessary.

The observation that trained motor units can be activated at different positions of a joint is related to the work of Boyd and Roberts (1953). They suggested that there are slowly adaptive end organs of proprioception, which are active during movements of a limb. They observed that the common sustained discharge of the end organs in movements lasted for several seconds after attainment of a new position. This might explain why a trained single motor unit's activity can be maintained during movements.

FIG. 54. Sample EMG of (a) the rectal, and (b) the rectal frequency of discharge of a motor unit in the right tibialis anterior during movements of the contralateral limb (time mark: 10-msec intervals). (From Basmajian and Simard, 1966.)
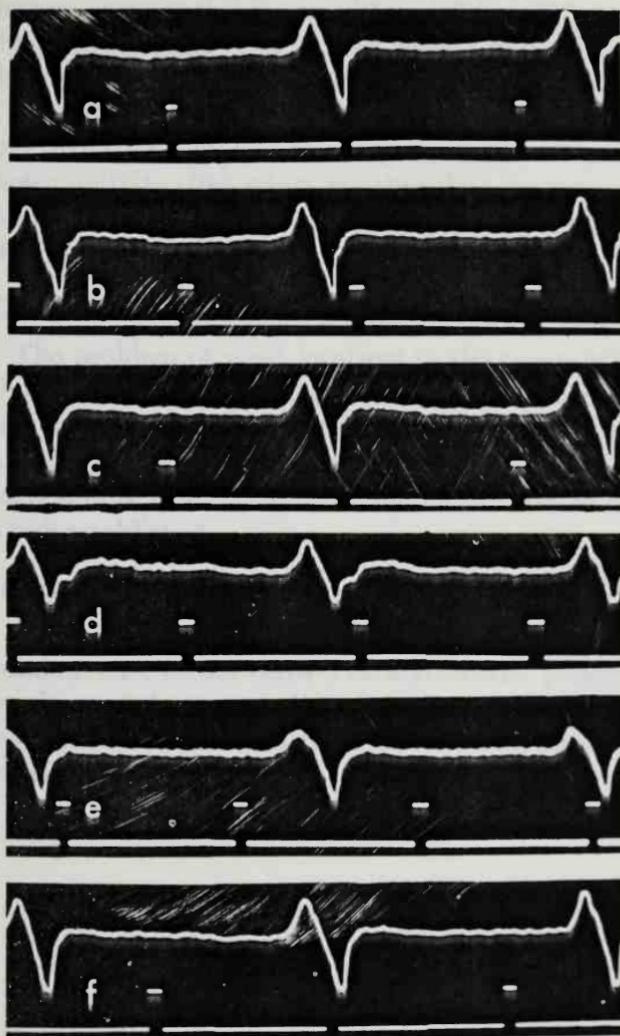
FIG. 55. EMG of a controlled motor unit potential at different "held" positions of the right lower limb: *a*, neutral; *b*, in lateral rotation at the hip; *c*, in medial rotation at the hip; *d*, dorsiflexion of the ankle; *e*, plantarflexion; *f*, toes extended. (Calibration: 100 μV, 100-msec intervals.) (From Basmajian and Simard, 1966.)

Fig. 55. EMG of a controlled motor unit potential at different "hold" positions of the right lower limb: a, neutral; b, in lateral rotation of the hip; c, in medial rotation at the hip; d, dorsiflexion of the ankle; e, plantar-flexion; f, knee extended. (Calibration: 100 μV, 100-msec intervals.) (From Basmajian and Simard, 1968.)
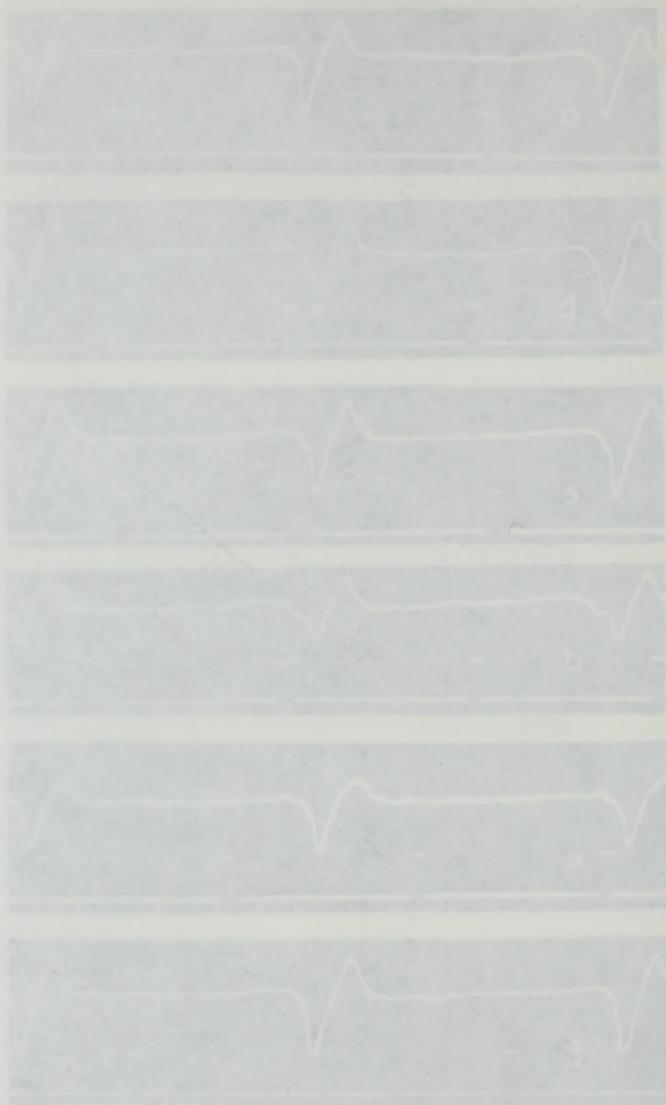
The control of the maintenance of a single motor unit activity during "proximal," "crossed" and "distal" joint movements in the same limb has been proved here to be possible providing that the technique of assistance offered by the trainer is adequate. The control over the discharge of a motor unit during proximal and distal joint movements requires a great concentration on the motor activity. But when one considers the same control during a "crossed" joint movement, there are even greater difficulties for obvious reasons.

The Level of Activity of Synergistic Muscles

The problem of what happens to the synergistic muscles at the "hold" position or during movements of a limb has been taken into consideration only in a preliminary way. The level of activity appears to be individualistic. Active inhibition of synergists is learned only after training of the motor unit in the prime mover is well established.

Practical Applications

Many applications are emerging for the use of motor unit training, e.g., in the control of myoelectric prostheses and orthoses, in neurological studies and in psychology. Very recently a novel application for treatment of reading disorders has been reported ().

Motor Nerve Conduction Velocity and Residual Latency

I̲NSEPARABLY wrapped up in function with the skeletal muscles are their motor nerves. The use of human nerve conduction velocity in studying abnormal states was introduced by Harvey and Masland (1941). Their technique which has been followed with minor variations by others consisted of recording action potentials from the hypothenar muscles following electrical stimulation of the ulnar nerve (figs. 56, 57). A simple and clear description of technique is given by Lundervold, Bruland and Stensrud (1965).

Hodes, Larrabee and German (1948) adapted this technique to the study of nerve conduction velocity as well as the action potentials of normal and abnormal nerves. Stimulating the ulnar nerve first at the elbow and then at the wrist while recording action potentials of the abductor digiti minimi, they determined the difference between the two latencies of response. This difference in latencies divided by the distance between the two points of stimulation yielded an accurate measure of the conduction velocity of the most rapidly conducting fibres in the nerve. Assuming
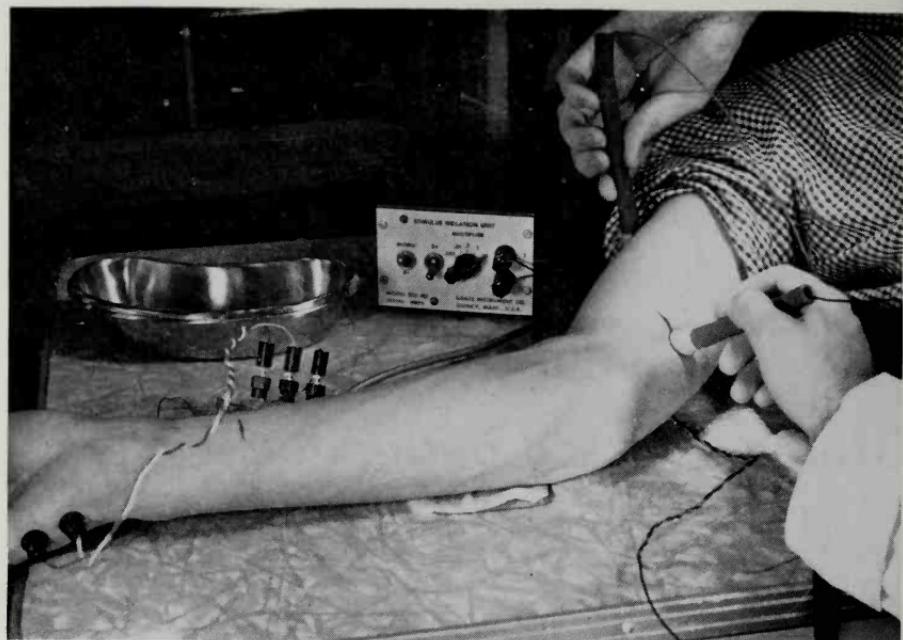
Fig. 56. Electromyographic electrodes on hypothenar muscles and stimulating cathode on ulnar nerve above the elbow. Black mark above wrist is site for other stimulation point. (From Low, Basmajian and Lyons, 1962.)

the speed was constant, Hodes *et al.* calculated the time that should be taken by the impulse to reach the muscle, and found that this was always less than the measured latency of the muscle action potential. Therefore, there is a small "residual latency" caused by either a slower velocity in the finer terminal portions of the nerve, or a delay at the neuromuscular junction, or a combination of these two factors. Indeed, Trojaborg (1964) has shown that the conduction velocity falls in the distal part of the median and ulnar nerve trunks. Spiegel and Johnson (1962) hold the opposite view.

In a series of papers, Magladery, McDougal and Stoll (1950a, b, c) extensively analyzed patterns of electrical activity evoked by stimulation of mixed peripheral nerves in human limbs. Their results indicate a slowing of the impulse in distal portions
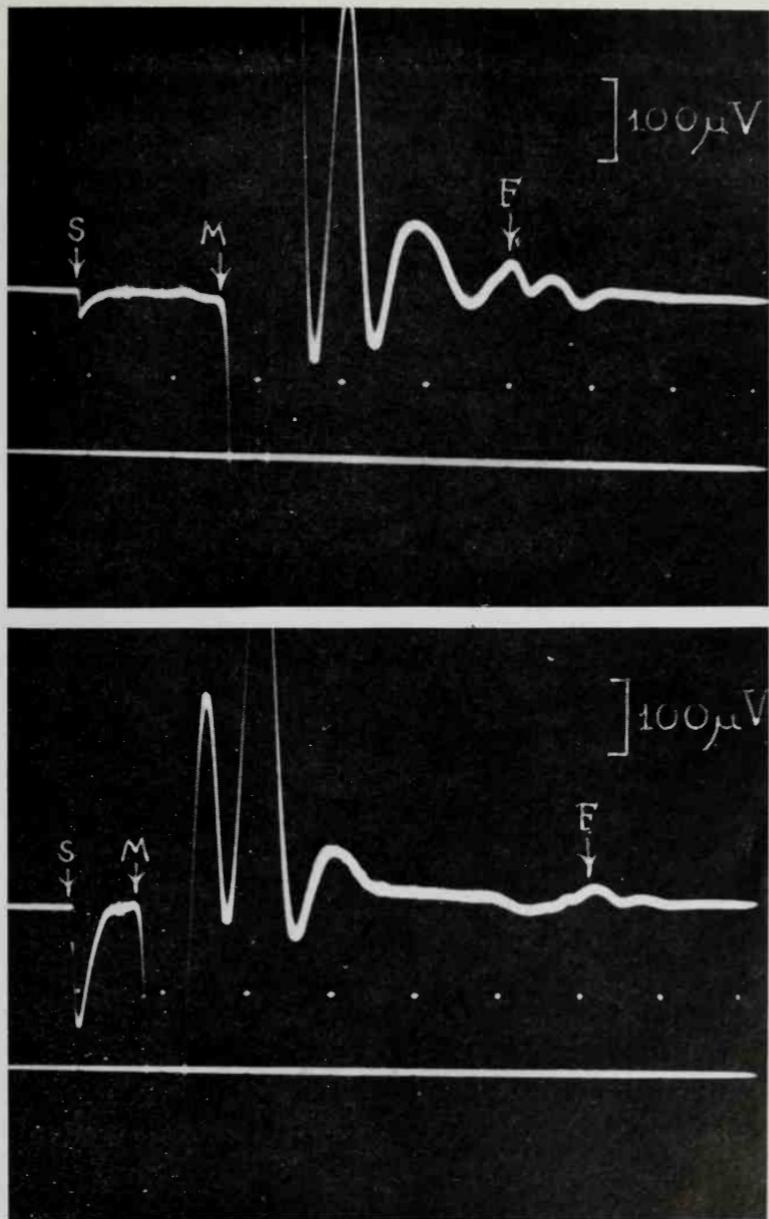
FIG. 57. Upper record, stimulus above elbow; Lower record, stimulus above wrist. Conduction time from stimulus (S) to the start of a muscle twitch (M) can be measured by comparing with the time signal (series of white dots at 5-msec intervals). (From Low, Basmajian and Lyons, 1962.)

of both motor and afferent nerve fibers, which accounts for a portion of the residual latency as described by Hodes *et al.*

Norris, Shock and Wagman (1953) determined ulnar nerve conduction velocities and "residual latencies" in 25 subjects ranging in age from 20 to 90 years. They found a decrease in velocity but no change in residual latency with increasing age.

Normal minimum values in average adults (rounded out, in metres per second) for various human nerves are: median and ulnar, 47 M per sec; deep peroneal, 38 M per sec; posterior tibial, 39 M per sec (Schubert, 1963). The mean velocity for the radial nerve is 56 M per sec according to Downie and Scott (1964), but it is 66 to 74 M per sec according to Gassel and Diamantopoulos (1964). The mean velocity in the sciatic nerve is 51 M per sec when abductor hallucis is recorded, and 56 M per sec when a shorter length of nerve is studied, i.e., when gastrocnemius is used for recording (Gassel and Trojaborg, 1964).

Mayer (1963) gives the following motor conduction velocities for the age group 10 to 35 years, which I have rounded out to the closest whole number:

Median: wrist-elbow—59 ± 4, and elbow-axilla—66 ± 5 M per sec

Ulnar: wrist-elbow—59 ± 4, and elbow-axilla—64 ± 3 M per sec

Common peroneal: 50 ± 6 M per sec

Posterior tibial: 46 ± 4 M per sec

In a much older age group (51 to 80 years) the velocities were lower by about 4 or 5 M per sec in almost all the above categories.

One always must apply "average normal" and "minimum" velocities with caution to individual cases. A wide fluctuation is possible during one session or from day to day as shown by our experiments, described below, and those of Christie and Coomes (1960). With variable physical factors playing a very real rôle, considerable error can creep into the results (Schubert, 1964).

LaFratta and Smith (1964) have shown that, on the average, conduction velocities are greater in women that in men although

the overlap shown in their graph seems quite large. They also found a slight decline in velocity with the older age groups.

The use of these emg methods to determine slowing in nerves affected by injury and various neuropathies has been discussed by Johnson and Olsen (1960) and Bastron and Lambert (1960), and by others. In thorough articles, Thomas (1961) and Dunn *et al.* (1964) reviewed the progress made in the clinical applications of these techniques. The purpose of this chapter (and, indeed, this book) is to avoid purely clinical discussions while providing a solid foundation of information about normal neuromuscular function as revealed by this application of EMG. One does this reluctantly for the recent clinical literature on conduction velocity is profuse, interesting and easily documented.

Our detailed study of normal conduction velocity and residual latency, carried out on volunteers over a period of hours, showed that conduction velocity in the motor fibres of the ulnar nerve between the elbow and the wrist fluctuates considerably, sometimes rather widely, from time to time in any individual (Low, Basmajian and Lyons, 1962). Therefore, single clinical estimations must be viewed with caution. Residual latency, a function of the delay in the terminal neuromuscular apparatus, also shows a fluctuation with time. Nevertheless, the study of the residual latency offers a new tool in the investigation of neuromuscular function. It deserves wider investigation, but to date it has been neglected.

The most striking observation in individual experiments was the fluctuation in conduction velocity. In individual subjects, velocities measured 15 min apart fluctuated by as much as 8 M per sec. Generally, the first two or three determinations (during the first 30 min of an experiment) tended to be higher than those that followed. Aside from this (inconstant) tendency for the velocity to decrease as the experiment progressed, values did not vary in a predictable way.

Because the temperature of the limbs was not controlled, temperature variations may account for some of the differences ob-

served between individuals and for some of the differences from time to time in the same person. Such variations were considered and deliberately accepted from the start so that the results might be directly comparable to determinations made on patients in routine diagnostic clinics where elaborate temperature control is impractical.

Our mean control value for the conduction velocity in the ulnar nerve, which is 56.3 ± 4.2 M per sec, agrees closely with values quoted in the literature, that given by Thomas, Sears and Gilliatt (1959) for the ulnar nerve being 56 ± 4.6 M per sec.

No one has commented previously on the fluctuation in conduction velocity with the passage of time in normal subjects. Reasons for the irregular fluctuations are not evident in the literature. Undoubtedly, progressive cooling of the forearm occurs as it lies exposed during an experiment, but, as explained before, temperature changes can be only a part of the explanation.

Changes in blood flow, variations in metabolic processes of the nerve or nearby muscle, or changing influences from the central nervous system all must contribute to the fluctuations. An important implication of their occurence is that we should be cautious in making only one or two determinations in a brief period to compare with "normal" or "abnormal" values. Johnson and Olsen (1960) state that their whole procedure takes ". . . five or ten minutes in a co-operative patient." None of the other writers report exactly what time is involved in the determination of their velocities. Sources of error in routine "diagnostic" tests are many and complex. Gassel (1964) incriminates the following: recording of potentials arising from muscles at a distance from electrodes, anomalous innervation, and spread of stimuli other than that over which the recording electrodes are placed. Simpson (1964) also warns against facile acceptance of results.

Nerve conduction velocities may be influenced by various conditions other than neurological diseases and by pharmacological influences. For detailed reports (which would be out of place in this book) one should refer to the following: the effects of chronic alcoholic polyneuropathy—Mawdsley and Mayer (1965); the acute effects of ethanol—Low, Basmajian and Lyons (1962); effects

of acute drug intoxication—Pihkanen, Harenko and Huhmar (1965).

Residual Latency

The mean of our control residual latencies was 1.52 ± 0.21 msec. This is somewhat lower than the other three mean values of residual latency in adults reported in the literature. Hodes, Larrabee and German (1948), Norris, Shock and Wagman (1953), and Bolzani (1955) gave values of 2.2, 1.7 and 2.68 msec respectively.

Like the values for conduction velocity, the residual latencies determined in each person fluctuate throughout an experiment lasting several hours. They tend to drop slightly, probably for the same sort of reasons that cause variations in conduction velocity. Only one paper comments on any positive change in residual latencies during experiments. Hodes, Larrabee and German (1948) report that in regenerating nerves (ulnar and median) following suture, the residual latencies were greater than the values for the same nerves under normal conditions. At the same time, they found that nerve conduction velocity was slowed. In a study by Norris, Shock and Wagman (1953), performed on a large number of subjects from 50 to 90 years of age, the velocity of conduction in the ulnar nerve decreased with increasing age, but the residual latencies remained unchanged.

Before concluding this chapter, a more comprehensive definition of "residual latency" than that offered by other writers must be made by discussing its elements. An important component of the residual latency must be the time taken for the muscle to respond to depolarization of the endplate. The residual latency must also include a short time taken by the muscle action potential to pass beneath the proximal recording electrode because muscles have a slow conduction velocity ranging from 1.3 to 4.7 M per sec, as shown by Ramsay (1960), and Eccles and O'Connor (1939). With surface electrodes, this factor is extremely small because they are placed over the area of innervation and they gather potentials from a relatively wide area.

Another component of the residual latency, the slowing of the

impulse in the fine terminal fibres of the nerve, has been calculated by Eccles and O'Connor (1939) to be about 0.2 msec. There is a fourth and perhaps the most significant component: the time consumed by neuromuscular transmission or the "synaptic delay." Direct measurements of this delay give values of about 0.5 msec (Eccles and O'Connor, 1939). According to Nachmansohn (1959) and Fatt (1959), this delay must be due to the time taken by electrical events in the nerve ending causing the release of acetylcholine and the corresponding build-up of the post-synaptic potential. The transmission of acetylcholine across the 500 Å gap cannot be a factor in the delay since Eccles and O'Connor estimate that this process should take no more than 10 microsec.

Thus, the latent period from the arrival of the impulse at the fine terminal nerve branches to the beginning of the muscle action potential is composed of the four factors discussed above. This time has been measured directly: in mammalian striated muscle it is approximately 0.85 msec (Eccles and O'Connor, 1939). The values for residual latency determined in our experiments are of the order of 1.5 msec; therefore, they must include factors in addition to the four previously mentioned.

According to some authors (Magladery and McDougal, 1950; Gilliatt and Thomas, 1959) there is a decrement in conduction velocity along a nerve in an extremity. Thus the distal portions conduct more slowly than proximal segments of the same nerve. If this is true, then the assumption that the velocity of the impulse from elbow to wrist is the same as that from wrist to muscle must introduce an error in calculation of the residual latency by the accepted method (i.e., subtracting the calculated latency of response in the hypothenar muscles to a stimulus applied at the elbow from the observed latency). This is mentioned by Magladery and McDougal and probably it contributes most of the remainder of the residual latency. In our series this portion would be about 0.67 msec.

Muscle Mechanics

U NDER this chapter heading, we shall consider a number of miscellaneous electromyographic studies all concerned with the mechanics of muscular action. The matters dealt with are of fundamental importance though they have remained obscure until recent years.

Spurt and Shunt Muscles

By the application of mathematical analysis MacConaill (1946, 1949) has shown that skeletal muscles act as "shunt" or "spurt" muscles. A shunt muscle is one that acts chiefly during rapid movement and along the long axis of the moving bone to provide centripetal force. On the other hand, spurt muscles are those that produce the acceleration along the curve of motion (fig. 58). However, there has been a lack of experimental data to confirm or disprove his theories. Examination of the findings of certain of our electromyographic experiments on the flexors of the elbow joint (performed with other aims in mind) appear now strongly to confirm MacConaill's calculations and conclusions (Basmajian, 1959).
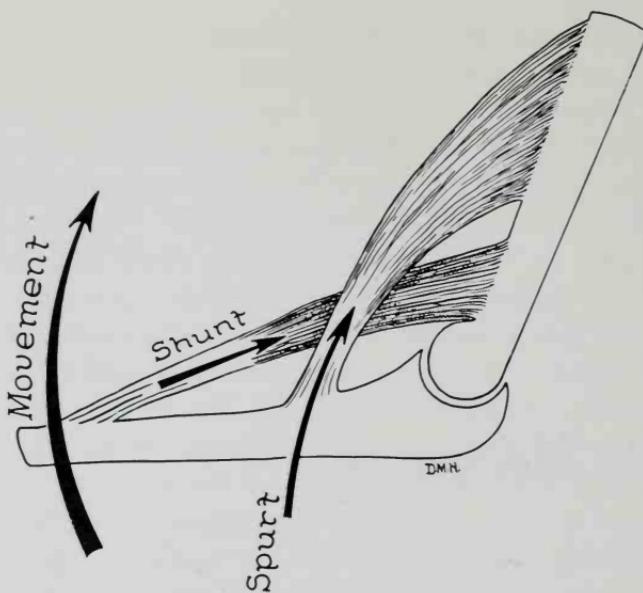
Fig. 58. Diagram of spurt and shunt muscles

During slow flexion of the elbow, with or without a load of 2 pounds, the brachioradialis was relatively quiescent in most of our subjects, while the biceps and the brachialis showed considerable activity. On the other hand, with quick flexion of the elbow the brachioradialis became very active in almost all the subjects.

During maintenance of flexed postures against the force of gravity, the biceps and the brachialis were almost always active while the brachioradialis was either inactive or only slightly active. Even the addition of a load of 2 pounds made little change in the activity of the brachioradialis.

During slow extension there was some slight activity in all of the muscles acting against the force of gravity with or without the added load. With quick extension, there was a general increase of activity, that in the brachioradialis being most pronounced.

On the basis of MacConaill's theory, the biceps and brachialis are chiefly spurt muscles at the elbow while the brachioradialis is chiefly a shunt muscle. In other words, except in complete extension, the former two muscles act mainly across the long axis

of the forearm providing the acceleration along the curve of motion (fig. 58). The brachioradialis, on the other hand, remaining more or less parallel to the forearm throughout the range of motion, acts mainly along the long axis of the forearm to provide the centripetal or shunt force and the required stabilization at the elbow joint (MacConaill, 1949).

Obviously, when the joint is not moving, the muscular forces along the bone and through the joint are equal to the total load of the limb. We know from common experience, confirmed by electromyography, that with no added weight and the limb hanging free this force is minimal. The load here is the weight of the limb beyond the elbow joint and the ligaments alone are adequate to carry it. The addition of a weight held in the hand increases the muscular activity in the biceps and the brachioradialis.

During very *slow* uniform flexion of the elbow joint, the shunt forces along the forearm will be approximately unchanging. Thus no great increase in the activity is required from the muscles for shunt or centripetal force. But if the flexion is rapid, a greater shunt or centripetal force *is* required. That force cannot be provided by the spurt muscles because they would impart a centrifugal acceleration along the tangent to the curve instead of producing a uniform rapid movement. Therefore the shunt muscles are called upon—indeed, must be called upon—for much greater activity. Our electromyographic findings confirm this. The brachioradialis, the typical shunt muscle, shows its greatest activity during uniform quick flexion of the elbow (fig. 59). During slow flexion and during the maintenance of flexed postures, it showed little or no activity even with a load of 2 pounds in the hand.

Our experiments showed that during both slow and quick extension of the elbow all the flexor muscles show considerable activity. During slow extension the "letting-out" function against gravity (p. 244) is called upon. However, during quick extension there would seem to be a need for complete inhibition of the antagonists. Experimentally, this did not occur. Barnett and Harding (1955) concluded from similar findings with the biceps
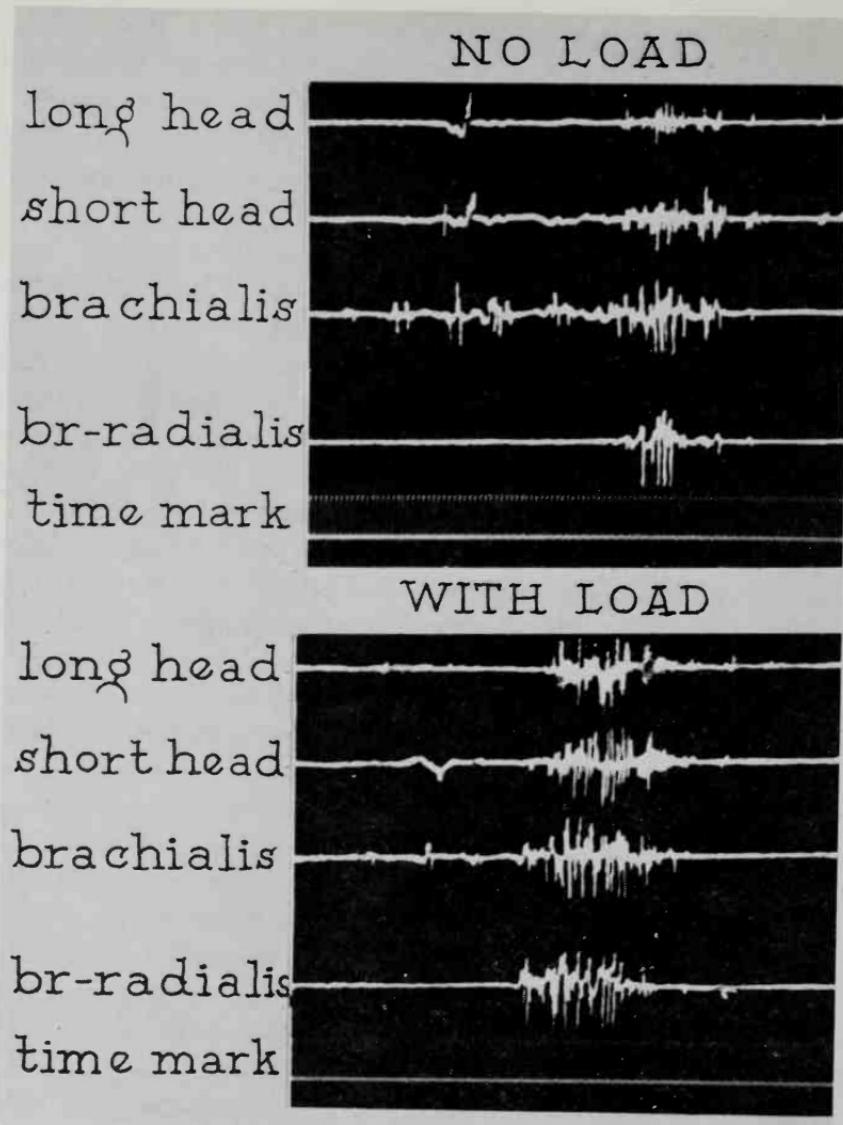
Fig. 59. EMG of main elbow flexors during quick elbow flexion. (Time mark intervals: 10 msec.)

alone that the antagonists come into strong contraction at the end of a whip-like movement due to the stretch reflex. It would appear that this protects the joint which otherwise would be injured.

In our work in this area (Basmajian and Latif, 1957) we found that during extension, a short, sharp burst of activity occurred in all three muscles—biceps, brachialis and brachioradialis. The brachioradialis in general was more active than biceps or brachialis during quick extension, providing further confirmation of MacConaill's mathematical theory. The basic requirement for a shunt muscle is to provide centripetal force during rapid movement in the circular path and so the direction of movement (regardless of whether it is in the direction of flexion or extension) is of no consequence.

Carlsöö and Johansson (1962) showed that when subjects fall to the ground on the outstretched hand all the muscles which surround the elbow joint are "strongly activated some tenths of seconds before the hand touches the surface." Consequently the musculature is prepared to protect the joint. This is partly a conditioned reflex and partly an unconditioned reflex arising from tonic neck and labyrinthine reactions. Independently, Watt and Jones (1966) found rather similar results in the lower limb. Emg activity in gastrocnemius began 80 msec before and 40 msec after the landing impact of the foot. They suggested that there is "a pre-programmed open-loop sequence of neuro-muscular activity virtually unaided by myotatic feedback." Myotatic reflexes were found to play no significant role in the deceleration for they came much too late.

The Controversy of Cocontraction vs Ballistic Movements

A good review of the concepts of cocontraction of antagonists and of ballistic movements is presented by Hubbard (1960). It is obvious that he rejects the former in favour of the latter and, although some of the evidence he cites is dubious, I must admit that our own work (some of which is reported above) tends to confirm his thesis in regard to fast movements. However, I am dubious about his concepts in regard to slow movements.

Cocontraction may be defined as the simultaneous contraction of both the agonists (or prime movers) and the antagonists, with a supremacy of the former producing the visible motion. Ballistic action may be defined as spurts of activity followed by relaxation

during which the motion continues through the imparted momentum. When applied to fast movements, the ballistics concept is acceptable if not fully proved, but when applied to slow, controlled movements it is unacceptable and quite unproved. For a useful— though very partisan—discussion of these problems the reader should see Hubbard's chapter in *Science and Medicine of Exercise and Sports* (1960). This section might be ended, however, with the famous verdict used in the Scottish Law Courts of "not proven."

Two-Joint Muscles

A two-joint muscle is one that not only crosses two joints but is also known to have an important action on both. The best examples are found in the thigh, crossing the hip and knee joints— rectus femoris, the hamstrings, gracilis and sartorius; but the anatomist is soon reminded that such important muscles as gastrocnemius, biceps brachii and the long head of triceps also cross two joints. Moreover, the tendons of many muscles of the forearm and leg cross an even larger number of joints. Generally, however, there is little confusion about the significant actions and functions of this last group, and the unsolved problems are centered more on the functions of the simple two-joint muscles. For lack of exact knowledge about these functions, they are usually dealt with superficially and, at best, theoretically.

Markee and his associates (1955), basing their conclusions on dissections of human cadavers and nerve-stimulation studies in dogs, stated that two-joint muscles of the human thigh can act at one end without influencing the other end. This is an astonishing concept that appeared to run directly against the logical understanding of muscular action. The explanation they offered is that the middle of the muscle bellies may be moored in various ways and the pull on each end can then be from the middle. If this were true, the functional implications would be extremely interesting and important and the clinical applications would be obvious. Because our group was engaged in a systematic study of the integrated functions and control of skeletal muscle, it became
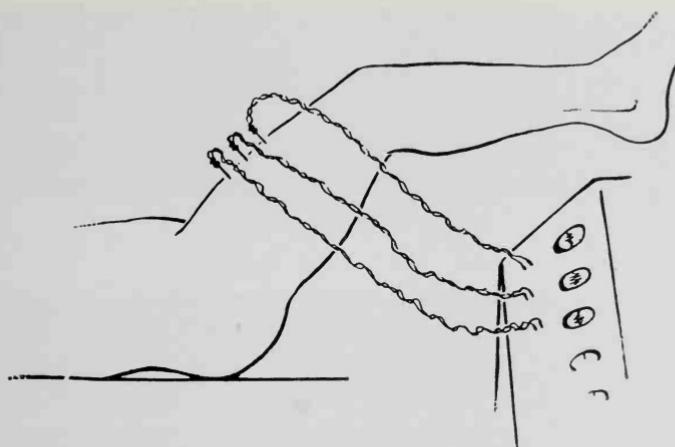
FIG. 60. Diagram of three needle electrodes in rectus femoris. (From Basmajian, 1957a.)

necessary to test the above thesis. A series of normal male volunteers were examined electromyographically, using a row of three to five needle electrodes in each muscle examined (fig. 60).

In the analysis of the activity in the proximal, middle and distal parts of the three muscles we may consider the significant movements of (1) the hip (i.e., proximal) joint and (2) the knee (i.e., distal) joint, disregarding whether these are flexion or extension.

In none of 21 muscles tested was there greater activity in the proximal part of the muscle when the proximal or hip joint was acted upon (figs. 61–64). Only one muscle in one subject, a semitendinosus, showed greater activity in the distal part when the distal joint (knee) was acted upon (the formula being middle > distal > proximal). However, this particular muscle showed the same formula with movements and postures of the hip, thus indicating that it has a relatively constant pattern regardless of the joint moved (Basmajian, 1957a). Miwa, Tanaka and Matoba (1963) confirmed these findings in a similar study.

The thesis put forward by Markee and his colleagues appeared at first to be attractive and important, but the electromyographic results showed that it is completely untenable in the case of
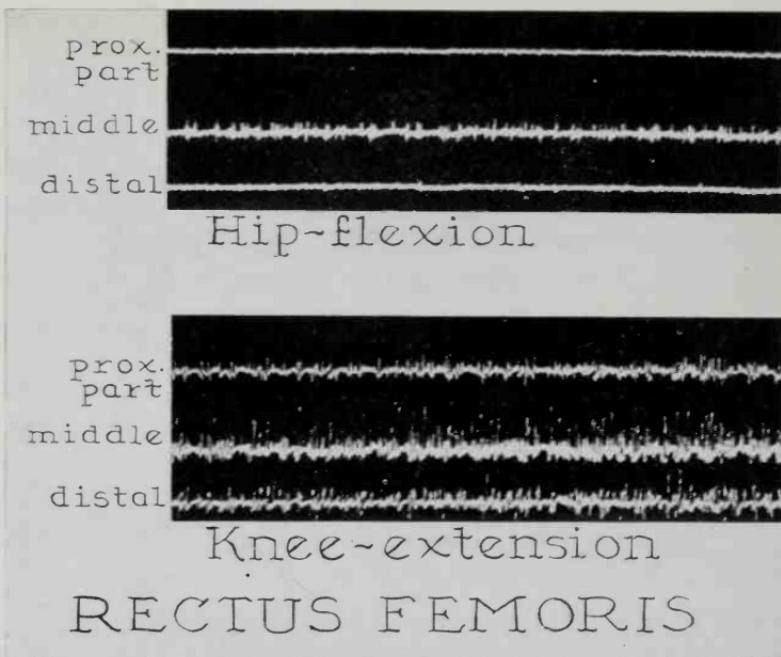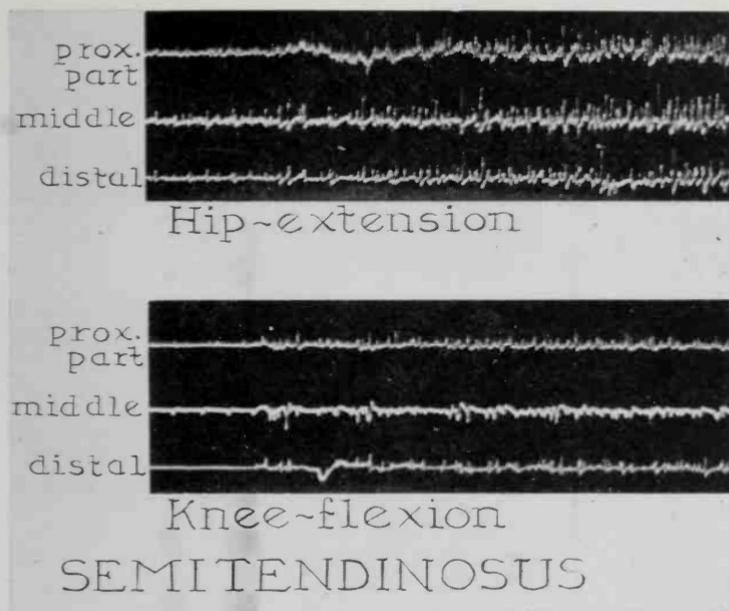
FIG. 61. EMG's of three parts of one subject's rectus femoris during hip flexion and knee extension (with other joint "relaxed"). (From Basmajian, 1957a.)

normal human two-joint muscles. In fact, the evidence is overwhelmingly in favour of the orthodox view. These muscles pull directly from one end to the other simply because all parts of the muscle belly contract together, the greatest activity being at the middle of the belly. What has been said above is not true for muscle bellies in parallel or parallel heads of large muscles. For example, in another study we have demonstrated that the two heads of biceps brachii may act relatively independently (Basmajian and Latif, 1957).

It may be argued that, in spite of the normal findings, occasions may arise when the proximal or distal part of a two-joint muscle does act independently. Such occasions must be very rare indeed. In fact, in upper motor neuron diseases the reverse is seen. In such cases the patient employs mass responses of many neighbouring, and often unrelated, muscles. It is difficult to imagine
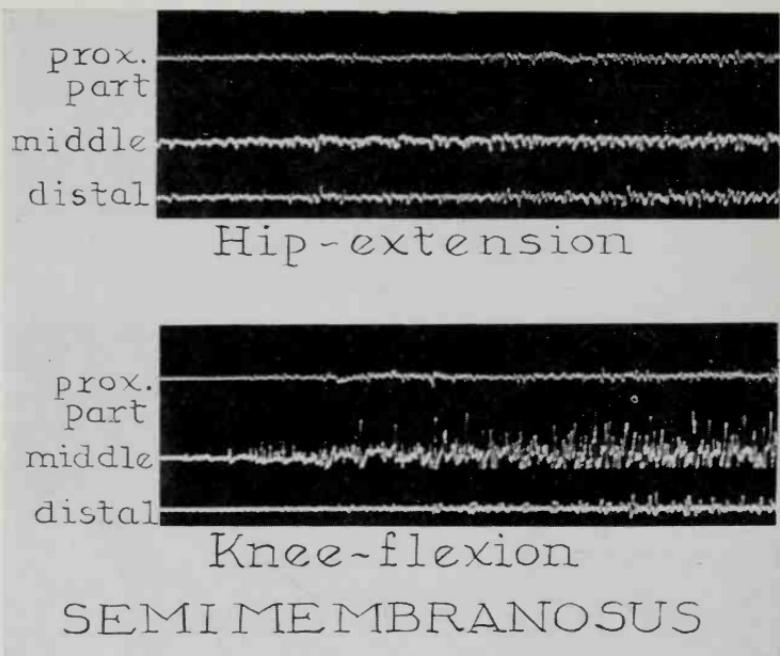
FIG. 62. EMG's of three parts of one subject's semitendinosus during hip extension and knee flexion (with other joint "relaxed"). (From Basmajian, 1957a.)

his employing one isolated muscle, let alone the proximal or distal half of one.

Finally, we must admit that under artificial experimental conditions, proximal and distal parts of two-joint muscles can be made to contract independently with relatively isolated effects. To accept this observation there is no need to invoke species differences and probably it would be reproducible in a human "preparation" if such were available.

Muscles Spared When Ligaments Suffice

Hardly any informed person would doubt that when gravity acts on the upper limb, and certainly when the limb carries a heavy load, muscles are the chief agents in preventing the distraction of the joints. Yet, recently, we have concluded that this is a false belief. We originally stumbled on this idea by accident

FIG. 63. EMG's of the three parts of one subject's semimembranosus during hip extension and knee flexion (with other joint "relaxed"). (From Basmajian, 1957a.)

while working on the electromyography of shoulder muscles with Dr. F. J. Bazant (Basmajian and Bazant, 1959). I have also extended our observations to include the elbow region.

Essentially, the fundamental conclusions can be made that ligaments play a much greater part in supporting loads than is generally thought and, in most situations where traction is exerted across a joint, muscles play only a secondary rôle. A review of our experiments on the foot (discussed on p. 149), adds further confirmation to the idea that normally ligaments and not muscles maintain the integrity of joints.

Our broader studies in the shoulder and elbow region will be described in greater detail below (p. 168) and the full details have been published previously (Basmajian and Latif, 1957; Basmajian and Bazant, 1959; Basmajian, 1961). This electromyographic

HIP KNEE

KEY: m=p=d m>p=d m>p>d m>d>p
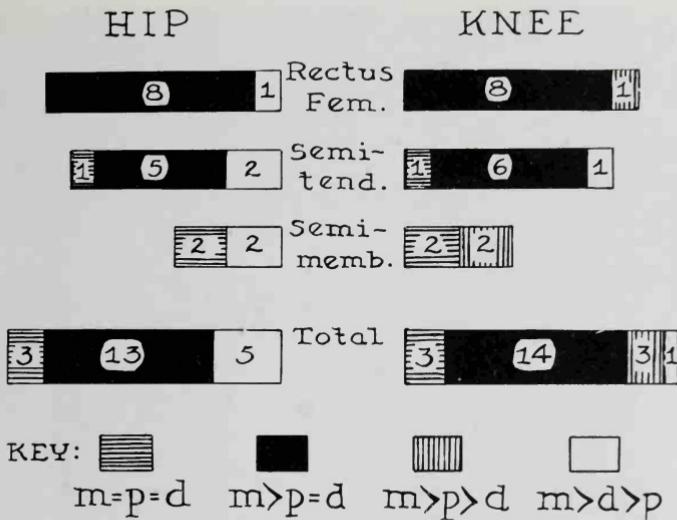
FIG. 64. Incidence of the four patterns of relative activity in the proximal (p), middle (m) and distal (d) parts of two-joint muscles during isolated action on the hip and on the knee. (From Basmajian, 1957a.)

investigation dealt with supraspinatus, infraspinatus, deltoid, biceps and triceps muscles in a series of normal persons. In the case of the deltoid, the needle in the anterior fibres was 2 inches below the lateral end of the clavicle; that in the middle fibres was 2 inches below the lateral border of the acromion; and that in the posterior fibres was about 3 inches below the spine of the scapula (fig. 65). The electrodes in the supraspinatus and the infraspinatus were placed in or near the middle of their bellies. The electrodes in the biceps were placed in the middle of the muscle whereas those in the triceps were placed in the middle of its long head.

The subject was seated upright with his arm hanging in the relaxed neutral position (the forearm midway between pronation and supination). Two types of load were added to the subject's arm. The first of these was a load of 16 pounds (lead weights held in the hand to the limit of individual endurance which proved to be a variable factor). The other load, less precise but more effec-
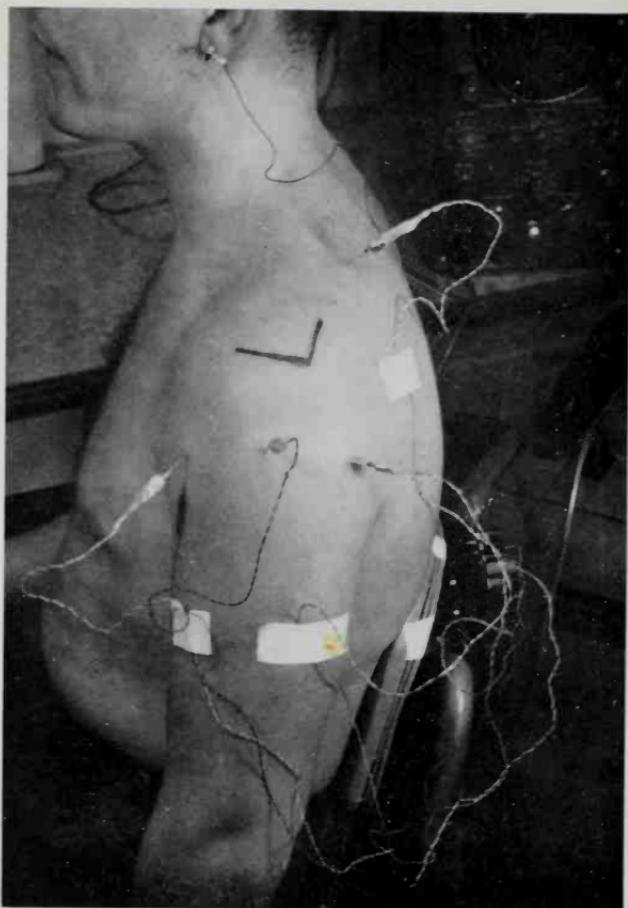
Fig. 65. Arrangement of needle electrodes in three parts of deltoid and the supraspinatus; subject in standard experimental position. Today, of course, we would use our fine-wire electrodes, but they would be invisible in the photograph. (From Basmajian, 1961.)

tive, was a sudden heavy sustained downward pull by one of the observers on the subject's hanging arm. In five persons a longitudinal pull was applied to the arm which had been abducted to the horizontal plane and completely supported by another observer so that no abduction activity was required of the subject's muscles.

For studies of the elbow, 24 adults were studied with electrodes
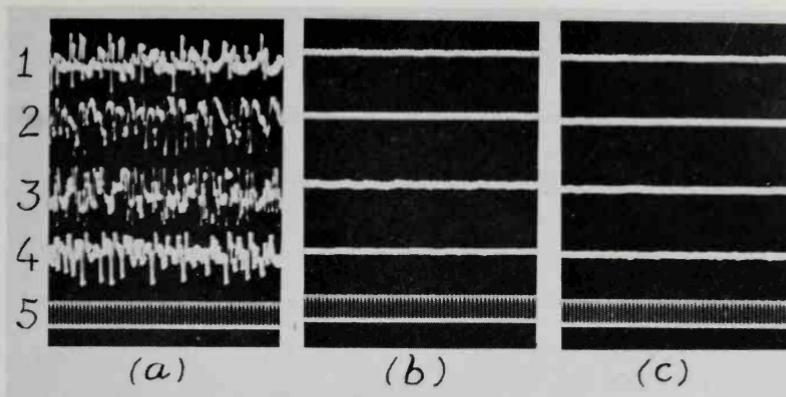
Fig. 66. EMG's, *a*, during abduction; *b*, unloaded arm hanging; and *c*, heavy downward pull applied to arm. Lines *1*, *2* and *3*—anterior middle and posterior fibres of deltoid; line *4*—supraspinatus; line *5*—time marker; intervals 10 msec. (From Basmajian, 1961.)

in both heads of biceps, in brachialis and in brachioradialis. In addition, the pronator teres muscles of eight other subjects have been studied more recently and our findings published (Basmajian and Travill, 1961).

In all instances, electromyographs were made with the subject seated upright and the upper limb hanging straight downwards in a comfortable position (fig. 65). Thus considerable numbers of biceps muscles were studied, some with heavy and moderate loads and others with light loads. In making the electromyograms of the pronator teres, only a strong downward pull was used as the added load since experience had already shown the ineffectiveness of lesser loads.

Contrary to expectation, the vertically running muscles that cross the shoulder joint and the elbow joint are not active to prevent distraction of these joints by gravity (figs. 66 and 67). Much more surprising is the fact that they do not spring into action when light, moderate or even heavy loads are added unless the subject voluntarily decides to flex his shoulder or his elbow and thus to support the weight in bent positions of these joints. Quite often, he may do this intermittently or, when uninstructed,
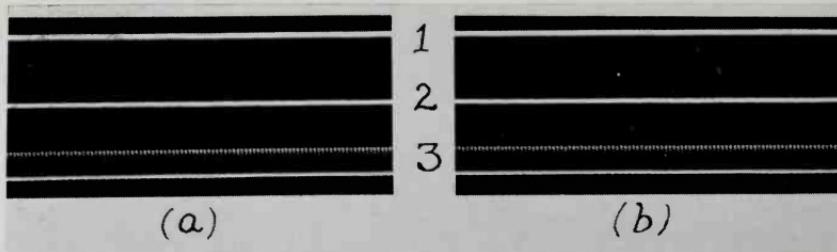
FIG. 67. EMG's of biceps (line *1*) and triceps (line *2*). *a*, hanging arm (unloaded), and *b*, heavily loaded. No change. (Line *3*, time marker, intervals 10 msec.) (From Basmajian, 1961.)

from the very onset. But it must be clear that such muscular action is a voluntary action and not a reflex one.

Even while the muscles were quiescent, our subjects rapidly felt local fatigue. What, then is fatigue in the heavily-loaded limb? Normally, it would be thought of as "muscular fatigue" but we see now that this is incorrect. The "fatigue" that is experienced probably originates from the painful feeling of tension in the articular capsule and ligaments, not from overworked muscles. In fact, as we have seen, the muscles need not be working at all.

An analogous situation occurs in the foot where we found, some years ago, that the muscles that are usually supposed to support the arches continuously were generally inactive in standing at rest (see p. 153). Independently Hicks (1954) showed by deduction that the plantar aponeurosis and plantar ligaments were the chief weight-bearers in this position. It would seem, then, that in the normal foot the fatigue of standing is not a muscular phenomenon.

The dual conclusion that articular ligaments suffice to prevent the downward distraction of joints in the upper limb and that fatigue is chiefly a form of pain in the ligaments appears to be of fundamental importance. It not only runs counter to "common sense" but it is of practical interest, for example, in explaining why dislocations by traction on normal limbs are rare. It should be noted especially that the capsule on the superior part of the shoulder joint including the coracohumeral ligament is extremely tight only when the arm hangs directly downward and the scapula

is in its normal position. The special mechanism that includes this ligament together with the supraspinatus muscle and the normal slope of the glenoid cavity will be described elsewhere (p. 168). When the shoulder joint is abducted or flexed, however, the capsule is extremely loose and the shoulder joint depends for its integrity on the well-known "rotator-cuff" muscles.

Quite independent from us, Stener, Andersson and Petersén of Göteborg, Sweden were arriving at similar conclusions in regard to ligament sparing from a different type of experiment in cats and man. When Andersson and Stener (1959) greatly increased the tension in the medial ligament of the knee of the cat in specially designed experiments, no reflex muscular contractions appeared in the muscles of the thigh as would have been expected if the usual hypothesis of "ligamento-muscular protective reflexes" were valid (fig. 68). Furthermore, they showed con-
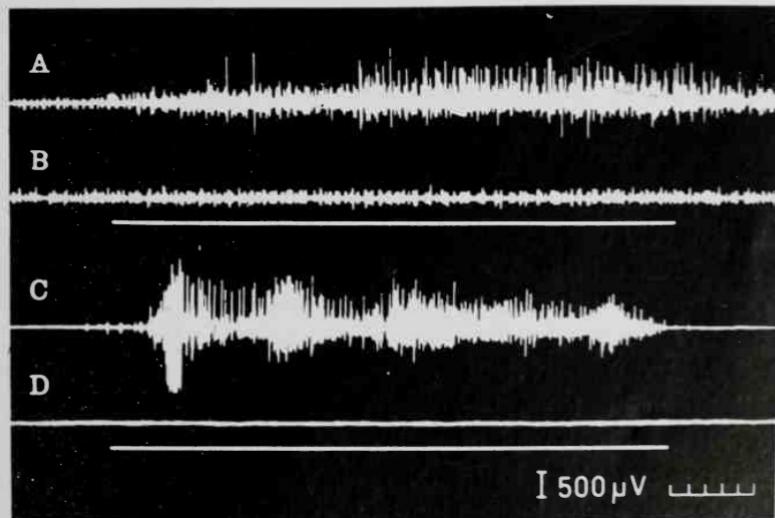
Fig. 68. EMG's of (decerebrate) cat from—*A* and *B*, vastus medialis; *C* and *D*, semitendinosus. *A* and *C* show reflex responses to stimuli other than stretch, to compare with the lack of response in *B* and *D* when the tendons were stretched by transverse loading (duration shown by straight horizontal white lines). (From Andersson and Stener, 1959.)

vincingly that the absence of reflex motor effects was *not* due to absence of afferent discharges which were well registered from the articular nerves.

Petersén and Stener (1959) carried the above experiments forward to human subjects again using the medial ligament of the knee. Their results were a complete vindication of the conclusions made in the animal experiments described previously. In addition their work suggests that if injured ligaments are pulled till pain results, muscles *do* show reflex contraction, but if the torn ligament is then anesthetized, they do not.

Following almost the same line of reasoning, deAndrade, Grant and Dixon (1965) distended human knees with non-irritating plasma (which emphasized the pressure phenomenon as opposed to pain). There was a definite and even marked inhibition of quadriceps contraction with a depression of motor unit activity. This is undoubtedly a reflex inhibition and helps further to explain the muscle weakness, atrophy and deformity that follows knee injury and disease.

Freeman and Wyke (1966) obtained a definite and chronic drop in reflex postural tonus in cats by cutting the sensory nerve supply of the knee joint capsule. The mechanoreceptors in the joint are involved in reflex muscular activity to maintain posture in quadrupeds; undoubtedly the same mechanisms occur in man as well. Surely all the above observations are of great importance in orthopedics and surgery of joint injury; they deserve wide attention.

Becker (1960) analyzed the responses of several muscle groups to pulls applied to them, i.e., passive stretch. Distinctive responses were obtained in the soleus and long head of triceps brachii. In normal persons, these had a definite relationship with the phase of the stretch cycle, being about 50 μv initially and diminishing on repeated stretching. In patients with diseases characterized by hyperirritability of the skeletal muscles, the responses in these muscles were greatly exaggerated. Gastrocnemius and the lateral head of triceps were found to not react to repeated stretching. A few vague scattered discharges were all that could be obtained in

the anterior tibial muscles, and these only in some of the abnormal cases. Becker feels that these responses indicate a special postural function of muscles that react to stretch.

Relation of EMG to Force or Tension

Isometrically contracting muscle most certainly shows a direct relationship between the mechanical tension and the integrated EMG. However, in the muscles of amputees, Inman, Ralston, Saunders, Feinstein and Wright (1951, 1952) found no direct quantitative relation when the muscles changed in length and they found no relationship between the muscle's inherent power and the EMG. With the studies involving rapid movement, they showed the mechanical tension lags (less than 0.1 second) behind the main burst of potentials.

Lippold and Bigland of University College, London, demonstrated in a fine series of papers (Lippold, 1952; Bigland *et al.*, 1953, 1954a, b) that, during a voluntary contraction, the tension is proportional to the measurable electrical activity both under isometric and—contrary to Inman *et al.* (above)—under *isotonic* conditions (figs. 69 and 70). They also showed that the gradation of contraction is brought about mainly by motor unit recruitment. The maximum tension produced by maximum tetanic indirect stimulation only equalled that developed in maximum voluntary contraction. The maximum with tetanic stimulation in their experiments with human subjects occurred at frequencies of 35 to 40 per second. (In a series of unreported experiments with rabbits, Hugh Lawrence and I found essentially the same thing.) Finally, Bigland and Lippold (1954a) demonstrated that tension, velocity and the EMG are interdependent, the integrated EMG providing a composite picture of the number and frequency of active muscle fibres.

Bergström (1959) of the University of Helsinki, Finland, has gone a definite step further than Lippold. After confirming the validity of the conclusion that the integrated potentials vary directly with the tension exerted, he showed that (in small muscles at least) these integrated potentials vary directly with the simple
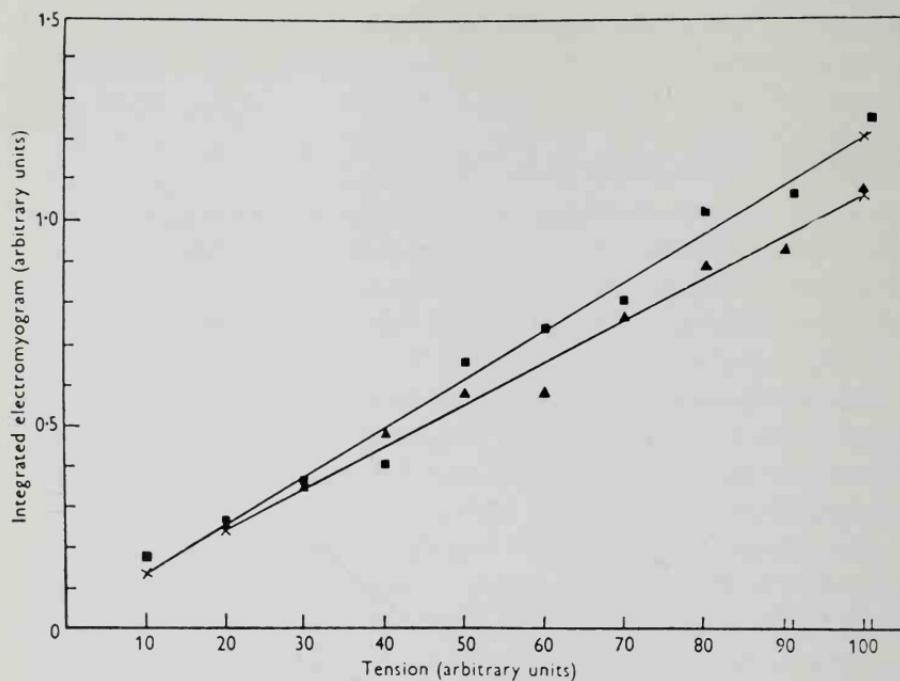
Fig. 69. The relation between EMG and tension during voluntary contraction in a single subject on two occasions. (From Lippold, 1952.)

frequency of the spike potentials (fig. 71). He concluded that the counting of motor unit spikes (fig. 72) can be used to estimate the electrical activity of, and thus the tension exerted by, the whole muscle. Close *et al.* (1960) have independently shown essentially the same thing using an electronic counting device.

In 1962, Bergström concluded from new experiments and calculations that there is a linear relationship between the number of impulses and the integrated *kinetic energy* of the muscular contraction. This work seems quite convincing (but *cf*. p. 66).

Ahlgren (1966) showed that integrated EMG's in the muscles of mastication rise linearly with the force of biting. A similar relationship is apparent between the impulse frequency from human intercostal muscles and the measured mechanical work of breathing (Viljanen, Poppius, Bergström and Hakumäki, 1964).

Acting as motors whose lines of pull change as the angle of the
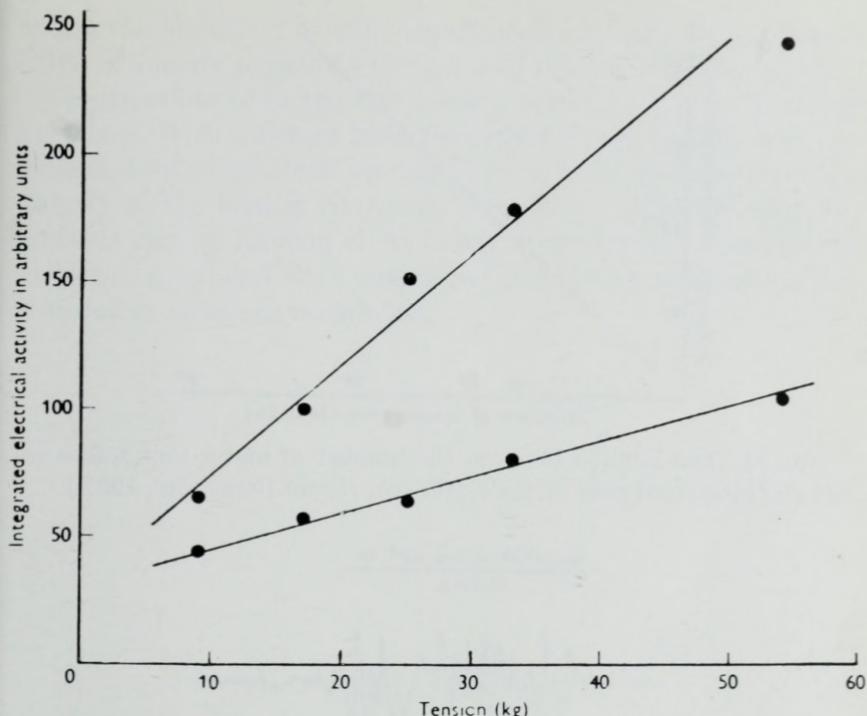
Fig. 70. The relation between integrated electrical activity (*via* surface electrodes) and tension in the human calf muscles. Shortening at constant velocity (*upper*) and lengthening at the same constant velocity. (From Bigland and Lippold, 1954a.)

joint is being constantly changed, individual muscles cannot be expected to act with constant force through a whole movement. The EMG reflects this logic. Further, reflex phenomena can be expected to contribute to the recruitment of various muscles that act upon a joint during any movement. This is illustrated by the findings of Miwa and Matoba (1959). They found that during slow flexion biceps brachii is much more active at certain angles of the elbow: it reaches a peak of activity when the elbow is at 160° and falls rapidly to almost *nil* at 90°; it increases again at maximal flexion. Miwa, Tanaka and Matoba (1963) find similar changes occur in the activity of muscles in the thigh.
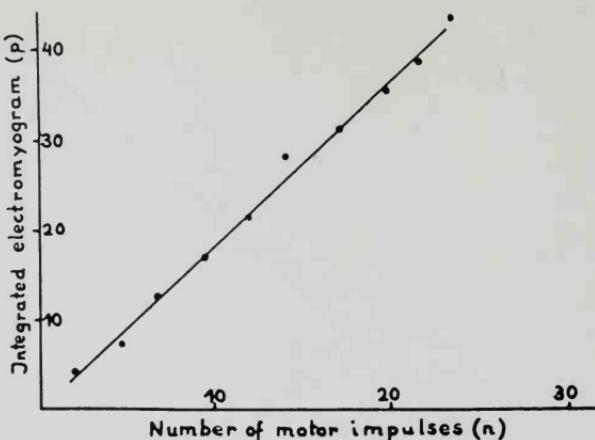
FIG. 71. The relation between the number of motor unit spikes (n) and the integrated area of the EMG (p). (From Bergström, 1959.)
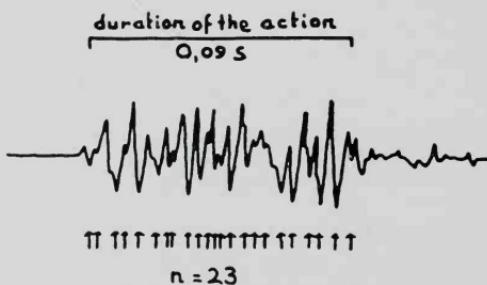
FIG. 72. Method of counting spikes (arrows showing the items counted). (From Bergström, 1959.)

With the angle of the joint unchanged, there is a linear relationship between the strength of a muscle and the amplitude of the integrated EMG, according to Liberson, Dondey and Asa (1962). They point out however—and this should be emphasized repeatedly—that the integrated output of *different* muscles cannot and must not be compared. Further, when the angle of the joint reaches certain limits, the results even within the same muscle may not accurately reflect the force exerted. The shape and orientation of certain muscles seem to complicate the picture further.

Bouisset, Denimal and Soula (1963) were able to show that

within the limitation of their experimental set-up, the integrated
EMG is linearly related to the speed of muscular shortening dur-
ing contractions of biceps and triceps, both flexing and extending
the elbow. With constant load, the activity rises linearly with ac-
celeration; with constant maximal acceleration, the activity rises
directly as the load is increased. One cannot help but echo the
cautious view of Ralston (1961): only under restricted conditions
can force, speed and work output be judged from emg data either
recorded as spikes or integrated.
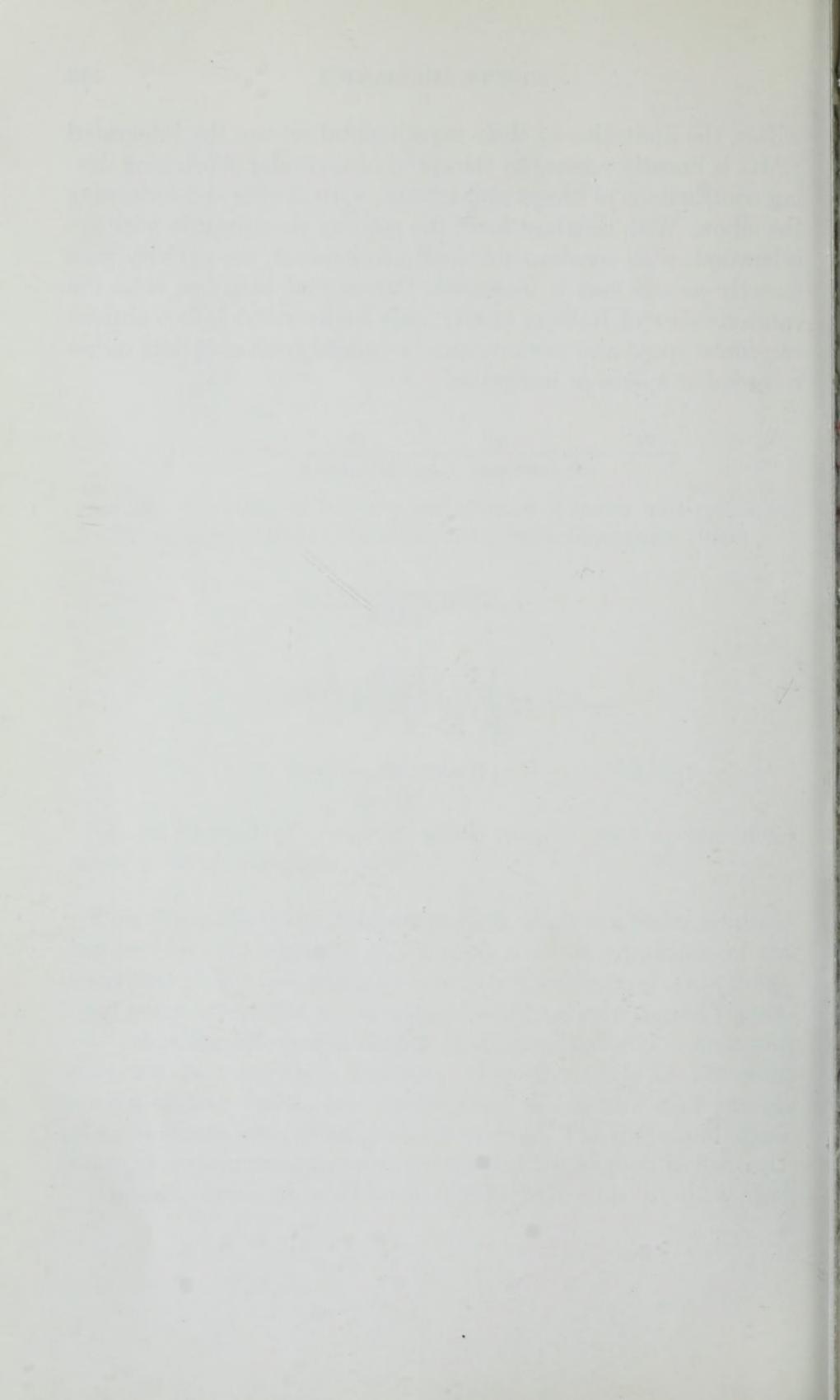
CHAPTER 8

Posture

ELECTROMYOGRAPHIC studies on postural muscles were begun
by various investigators soon after the modern form of the tech-
nique was introduced near the end of World War II. Previously,
it is true, rather crude attempts had been made to investigate the
function of muscle groups by picking up and recording the elec-
trical discharges that accompany the contraction of muscle.
However, these attempts were thrown into the shade by the rise
of modern electronics. Today, we must admit that, following the
epoch-making stimulation studies of Duchenne in the nineteenth
century, nothing very useful had been contributed to our knowl-
edge of human posture by primarily electrical techniques until
the past two decades.

It will be seen, therefore, that, narrowly defined, the subject
to be discussed does not have a long history. Nonetheless, it
cannot be divorced from an historical background because the
object of our enquiry, i.e., posture, has been the concern of
anatomists, biologists and orthopedic surgeons for many years.
Therefore, this discussion will not be confined strictly to electro-
myography; neither will it be confined to studies on posture in its
extremely limited sense.

The definition of posture can be altered for the sake of argument according to how broad or how narrow one wishes to make it. In the narrowest sense, posture may be considered to be the upright, well-balanced stance of the human subject in a "normal" position. In this sense, the electromyography of posture would deal with the maintenance of the erect subject's position against the force of gravity. The present account will, of necessity, emphasize this aspect of posture, but a broader, more generous and more palatable definition would not exclude the multiplicity of normal (and abnormal) standing, sitting and reclining positions that human beings assume in their constant battle against the force of gravity. In the final analysis, the intrinsic mechanisms of the body that counteract gravity make up the essence of the study of posture. One of these, the muscular mechanism, shall be our chief concern.

Posture of the entire body may be considered as a unit, and because such a consideration is rather artificial, it has inherent dangers. They often lead to a facile neglect of the posture in those parts of the body which do not intercept the main line of gravity for the trunk and lower limbs. As a result, posture in the upper limbs, both while hanging freely downwards and in various other positions, too often gets ignored. In still another direction, the posture of the mandible may also be ignored by the general anatomist, but it certainly is emphasized by the orthodontist for whom it assumes a considerable practical importance.

The problems of static posture, then, revolve around the truism that the balance or equilibrium of the human body or its articulated parts depends on a fine neutralization of the forces of gravity by counter-forces. These counter-forces may be supplied most simply both internally and externally by a supporting horizontal surface or series of horizontal surfaces that are inert. The "easiest" posture in which a human being can achieve equilibrium with gravity is the recumbent one. We should not lose sight of the fact that this is our normal posture for the first year or so of our lives and for about half of our lives thereafter. When we lie down, we

POSTURE

bring the centre of gravity of the entire body as well as any or all
of its parts closest to a supporting anti-gravitational surface.

Lundervold (1951) of Stockholm demonstrated by electro-
myography that healthy persons who do not tense their muscles
can sit comfortably and relax in many positions, and can even
work in many different manners without pronounced increase in
muscular activity. Nervous subjects do not relax completely in
more than a few positions and they cannot change their individual
optimal working positions without a markedly increased exertion
of muscle power.

Returning to the support of the erect body, we find that in the
nineteenth century many laborious studies, some fruitful and
others not, were performed to determine the line of gravity and
the centre of gravity of the whole human subject. The simplest
estimate and the one that is most easily appreciated is that of
von Meyer (1868) who found that the weight-centre is situated
at the level of the second sacral vertebra. (On the surface of the
body this vertebra is at the level of the posterior superior iliac
spines.) In the coronal plane the exact point lies 5 cm or less be-
hind the line joining the hip joints, and, of course, it is in the
midline.

It will be seen that to maintain an equilibrium in the standing
posture with the least expenditure of internal energy, a vertical
line dropped from the centre of gravity should fall downward
through an inert supporting column of bones. This is the ideal
and it is surprising how closely the human supporting mechanism
approaches it, if only intermittently.

The idealized normal erect posture is one in which the line of
gravity drops in the midline between the following bilateral points:
(1) the mastoid processes, (2) a point just in front of the shoulder
joints, (3) the hip joints (or just behind), (4) a point just in front
of the centre of the knee joints, and (5) a point just in front of
the ankle joints (fig. 73). Muscular activity is called upon to
approximate this posture or, if the body is pulled out of the line
of gravity, to bring it back into line.

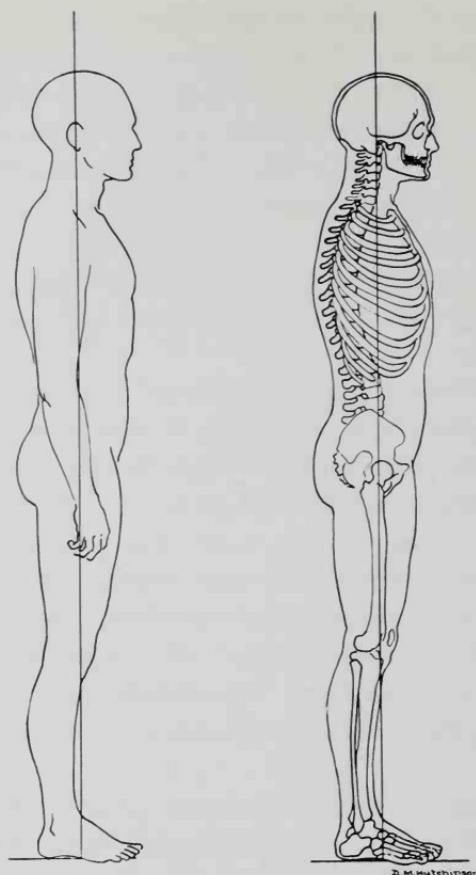Most people do not appreciate that, among mammals, man has

FIG. 73. Line of gravity in total erect man (see text)

the most economical of anti-gravity mechanisms once the upright posture is attained. His expenditure of muscular energy for what seems to the student of phylogeny to be a most awkward position is actually extremely economical. Most comparative anatomists certainly seem to be ignorant of this fact. A quadruped that is required to maintain the multiple joints of its limbs in a state of partial flexion by means of muscular activity demonstrates a much more wasteful anti-gravity machinery. An exception to this seems to be the elephant whose limbs serve as static columns to maintain an enormous weight. On the other hand, the specialization of the elephant's weight-bearing limbs is so great that it

cannot produce a true jump for even short distances. Relative
to its size, the muscles of its limbs are quite puny compared with
man's. The reason for this disproportion is that, unlike the ele-
phant, man is constantly challenging gravity by his continued
wide range of postures, and great power is not required to achieve
this. Thus we find that man's so-called anti-gravity muscles are
not so much to maintain normal standing and sitting postures as
they are to produce the powerful movements necessary for the
major changes from lying, to sitting, to standing. Therefore it is
wrong to equate the anti-gravity muscles of man with those of
the common domestic animals which stand on flexed joints.

In man, the column of bones that carries the weight to the
ground constitutes a series of links. Ideally, these links should be
so stacked that the line of gravity passes directly through the
centre of each joint between them. But even in man this ideal
is only closely approached and never completely reached—and
then only momentarily. As Steindler (1955) showed, a completely
passive equilibrium is impossible because the centres of gravity
of the links and the movement-centres of the joints between them
cannot be all brought to coincide perfectly with the common line
of gravity. In spite of this, I believe that Steindler and many
others have greatly exaggerated the amount of effort required to
maintain the upright posture. The fatigue of standing is em-
phatically not due to muscular fatigue and, generally, the muscu-
lar activity in standing is slight or moderate. Sometimes it is
only intermittent. On the other hand, the posture of quadrupeds,
which is maintained by muscles acting on a series of flexed joints,
is highly dependent on continuous support by active muscular
contraction. Of course the same is true for the human being in
any but the fully erect standing posture.

Dudley Morton (1952) anticipated much of what has been
recently proved by electromyography. Unfortunately, he incor-
rectly ascribed the fatigue of prolonged standing to a continuous
activity of the muscles. This error is surprising because his calcula-
tions are otherwise quite valid. What he and others have ignored
is that walking is usually less fatiguing than standing. Although

extreme exertion can produce muscular fatigue, most fatigue in the lower limbs caused by standing is more intimately associated with the inadequacies of the venous and arterial circulation and with the direct pressures and tensions upon inert structures.

As Carlsöö (1961) has emphasized, certain muscle groups can be called "prime postural muscles." Among these are the neck muscles, sacrospinalis, hamstrings and soleus. Carlsöö also points out that such postural muscles are among the most powerful. However, one must note that this is not an absolute case.

Carlsöö found that during stooping most persons failed to use a well-balanced position, placing "too large a part of the load on the anterior part of the foot." They then powerfully engaged the soleus, gastrocnemius, flexor hallucis longus and peroneus. "Others placed too much of the load on the heels, so that the tibialis anterior and the peroneus muscles, which do not well tolerate continuous loading, were strongly activated."

Carlsöö considers the shifting from foot to foot in ordinary standing as a relief mechanism. "By assuming asymmetric working postures, and using the right and left leg alternately as the main support, the leg muscles are therefore periodically unloaded and relaxed." One should add that the relief to the inert structures is perhaps even more significant (p. 229).

Posture of Lower Limb

LEG. The function of the large muscles of the leg in relationship to posture has been studied by a number of investigators and recently made the main subject of a book by Joseph (1960). Not infrequently, different conclusions have resulted from different techniques. For example, Joseph and Nightingale (1952, 1956) concluded from their study with surface electrodes that the soleus of all persons and the gastrocnemius of many show well-marked activity when the subject is standing at ease; and meanwhile, they claimed, the tibialis anterior is "silent." Their explanation, which agrees with the conclusion of Åkerblom (1948), is that the line of gravity is found to fall in front of the knee joint and ankle joint, necessitating activity in gastrocnemius. On the other hand, we showed with needle electrodes that there is actually a wide

range of findings for each of these muscles, though, indeed, the
posterior calf muscles are generally much more active than the
tibialis anterior (fig. 74, *B*). Furthermore there is frequently a
periodicity in the activity and this is apparently related to an
almost imperceptible forward-and-backward swaying of the body
(Basmajian and Bentzon, 1954). Periodicity was first noted in
this regard by Floyd and Silver (1950) and it has been commented
on by Portnoy and Morin (1956) and others. Granit's (1960)
statement that, in general, soleus is tonic while gastrocnemius is
phasic may explain some of the discrepancies in the findings for
the leg reported above. Carlsöö (1964) finds activity regularly in
soleus during quiet, symmetric standing but never in tibialis
anterior. With a heavy load held either in front of the thighs or
carried on the back, activity becomes pronounced in soleus, ap-
parently to counteract the forward leaning of the body. Tibialis
anterior remains completely inactive.

As would be expected, any deliberate leaning forwards or back-
wards of a standing subject produces compensatory activity in
the muscles to prevent the occurrence of a complete imbalance
(fig. 74, *A-C*). A very finely regulated mechanism is in control
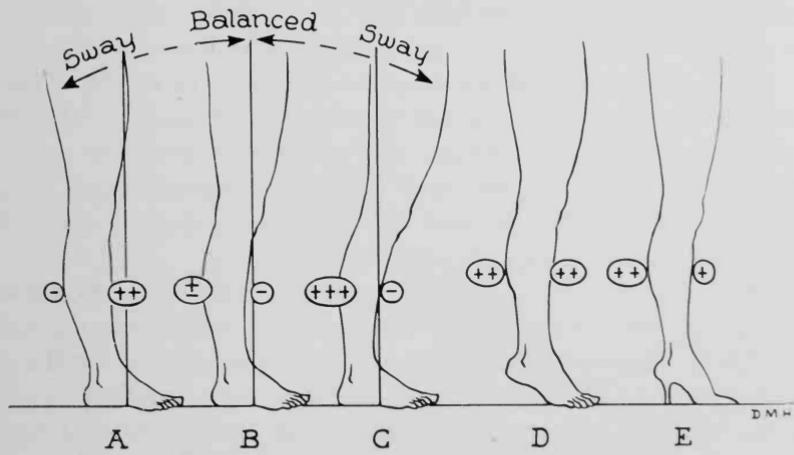
Fig. 74. Diagram of emg activity in anterior and posterior muscles
of the leg under differing conditions.

and the slightest shift is reacted to through the nervous system by reflex postural adjustments; sometimes the motor responses are so fine that they can only be detected electromyographically. Recently, Houtz and Fischer (1961) showed that these muscles respond to many influences such as postural changes, the shifting of body weight, and the resisting of external forces applied to the upper part of the trunk.

In women who wear high heels, there appears to be a modification of the muscular response. Both our group (1954) and Joseph and Nightingale (1956) found that the wearing of high heels increases the activity of the calf muscles of individual subjects, apparently due to a shifting forwards of the centre of gravity (fig. 74, E). One would have expected that in women wearing high heels the well-known compensatory spinal lordosis would be a sufficient adjustment. Apparently it is not.

THIGH. The muscles of the thigh obey the same rules as those of the leg. By and large, the activity during normal, relaxed standing is usually slight. Indeed, it may be absent in most of the muscles for varying periods of time. The reports of Weddell, Feinstein and Pattle (1944), Åkerblom (1948), Arienti (1948), Wheatley and Jahnke (1951), Floyd and Silver (1951), Joseph and Nightingale (1954), Portnoy and Morin (1956), Oota (1956a), Joseph and Williams (1957) and Jonsson and Steen (1966), and the work in our laboratory seem to agree in principle. These overlapping and detailed studies include most of the large muscles of the gluteal region and thigh, and no purpose would be served in recapitulating the details here. The main generalization to be extracted from all this is that the activity in these muscles is surprisingly slight during relaxed standing.

When subjects carry a load either held in front of the thighs or strapped to the back, Carlsöö (1964) found quadriceps remains completely inactive. Meanwhile, the ischiocrural muscles (hamstrings) show individual variations—from very active to completely inactive—apparently depending on the degree of flexion of the hip and on whether or not the line of gravity had been shifted anterior to the hip joint.

FOOT. The postural function of the muscles of the foot in relation to the normal support and the abnormal flattening of the arches has always posed a question of some fundamental interest. Using needle electrodes, we showed (Basmajian and Bentzon, 1954) that the intrinsic muscles are generally quiescent during normal standing but become extremely active when the subject rises on tip-toes and during the take-off stage of walking (fig. 75). This was confirmed in general by Sheffield, Gersten and Mastellone (1956) but it appears that others have not paid sufficient attention to this fundamental consideration in the posture of the foot.

In the past, the peroneal and tibial muscles have often been considered to play an important rôle in maintaining the longitudinal arches of the foot in standing. This theory seems to have been discredited by our findings and by the indirect contributory evidence of other investigators. During standing these muscles of the leg are generally quiescent. Furthermore, they remain inactive even when a subject suddenly lowers himself to a normal standing position from an elevated seated position. However, if in the standing posture the foot is obviously inverted by tibialis anterior, activity is quite intense. During locomotion, peroneal and tibial muscles show marked activity (fig. 74).
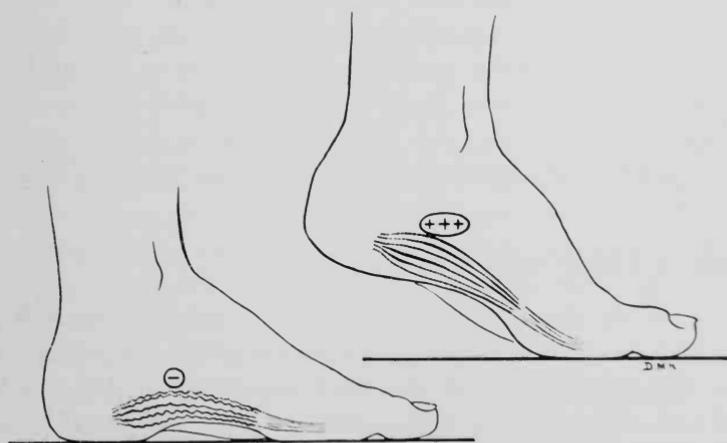
FIG. 75. Diagram of emg activity in intrinsic foot muscles (see text)

Apparently, the first line of defence against flat feet is a ligamentous one (Basmajian and Stecko, 1963). This is considered further on page 229. But the added stresses of walking require special mechanisms (Basmajian, 1955a, 1960). Independently, a similar view has been advanced by Dudley Morton (1952), who on the basis of various calculations predicted essentially the same thing. He showed that static strains upon the ligaments of the arch to sustain its elevated position are low in intensity and fall well within the capabilities of the ligaments. His calculations showed that only acute, heavy but transient forces (such as in the take-off phase of walking) required the dynamic action of muscle. Meanwhile, further confirmation was provided by Hicks (1951, 1954) who has demonstrated the importance of the plantar aponeurosis.

HIP AND KNEE. The hip and knee each has at least one muscle with a special postural function that can be demonstrated electromyographically. Experiments (Basmajian, 1958b) have shown that iliopsoas remains constantly active in the erect posture (in contrast to the large thigh muscles). It would appear that iliopsoas functions as a vital ligament to prevent hyperextension of the hip joint while standing (see p. 206). (The supraspinatus has a similar activity at the shoulder joint; see below.)

At the knee, Barnett and Richardson (1953) have shown a constant activity in the popliteus in the crouching or "knee-bent" posture. This apparently is related to a stabilizing postural function to help the posterior cruciate ligament prevent an anterior dislocation of the femur (fig. 76). There is no similar popliteal activity in the erect posture when dislocation is not threatening the joint.

Posture of Trunk, Neck and Head

SPINE. While standing erect, most human subjects require very slight activity and sometimes some intermittent reflex activity of the intrinsic muscles of the back according to Allen (1948), Floyd and Silver (1951, 1955), Portnoy and Morin (1956) and Joseph (1960). These authors showed that during forward flexion
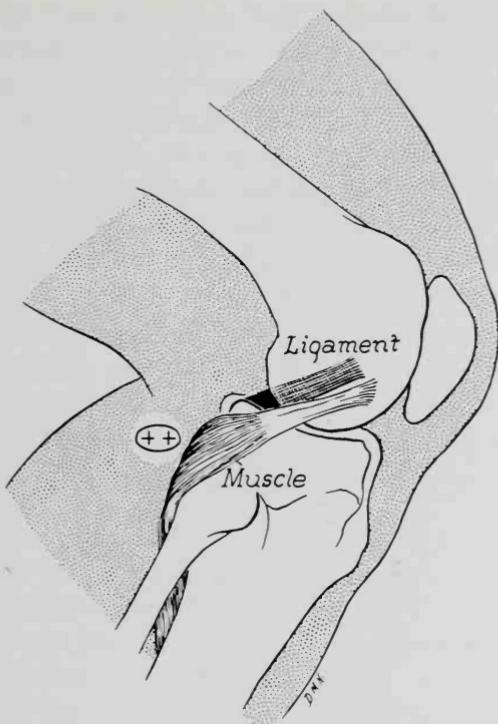
Fig. 76. Popliteus shows emg activity in the knee-bent stance

there is marked activity until flexion is extreme, at which time the ligamentous structures assume the load and the muscles become silent (fig. 77). Floyd and Silver (1955) proved (with both surface and needle electrodes) that in the extreme-flexed position of the back, the erector spinae remained relaxed in the initial stages of heavy weight-lifting. This observation appears to confirm strongly the dangers to the vertebral ligaments and joints of lifting "with the back" rather than with the muscles of the lower limb (see p. 246).

Asmussen (1960) first concluded from an emg study that continuous activity of the back muscles during standing is the rule because "the line of gravity passes in front of the spinal column." The last part of this conclusion is contrary to previous opinions

and requires confirming. Later Asmussen and Klausen (1962) modified the earlier extreme view to conclude that "the force of gravity is counteracted by one set of muscles only, most often the back muscles, but in 20 to 25 per cent of the cases the abdominal muscles. The line of gravity passes very close to the axis of movement of vertebra L4 and does not intersect with the curves of the spine as often postulated." Carlsöö (1964) regularly found activity in sacrospinalis in the symmetric, rest position.

More recently, Klausen (1965) investigated the effect of changes in the curve of the spine, the line of gravity in relation to vertebra L4 and ankle joints and the activity of the muscles of the trunk. He concluded that the short, deep intrinsic muscles of the back must play an important rôle in stabilizing the individual intervertebral joints. The long intrinsic muscles and the abdominal
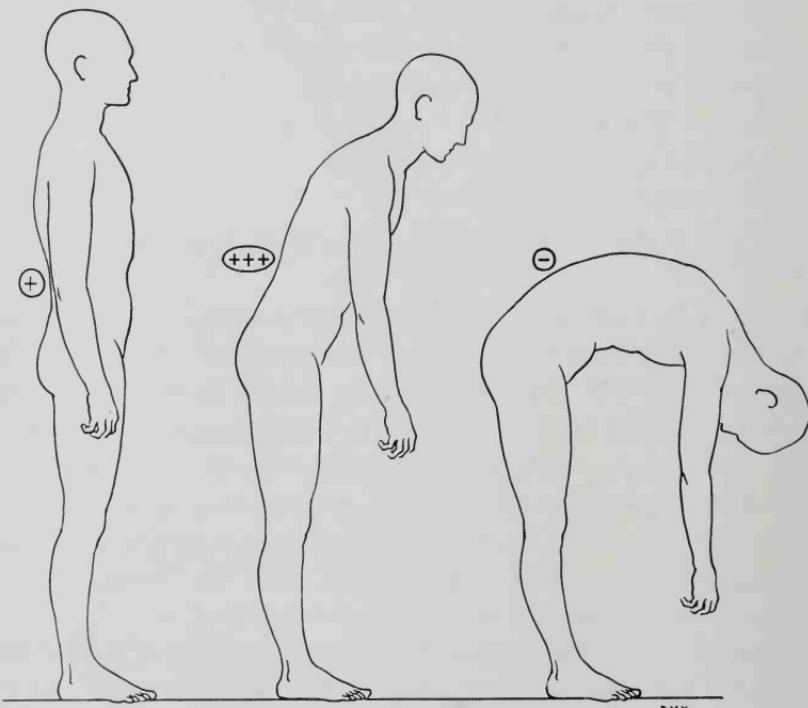
FIG. 77. Diagram of activity in erector spinae during forward bending (see text).

muscles stabilize the spine as a whole. An increased pull of gravity always is counteracted by increased activity in one set of muscles only, i.e., either in the back or anterior abdominal wall.

Placing a load high on the back automatically causes the trunk to lean slightly forward. The increased pull of gravity is counteracted by an increased activity in the lower back muscles. A load placed low on the back reduces the activity of the back muscles. This last finding was duplicated by the independent work of Carlsöö (1964). However, Carlsöö found increased activity in sacrospinalis with a load held in front of the thighs. Thus the position of the load—either back or front—either aids the muscles or reflexly calls upon their activity to prevent forward imbalance. Nachemson (1966) finds the vertebral part of psoas major helps to maintain the posture of the lumbar vertebrae.

ABDOMEN. During relaxed standing, only slight activity has been recorded in the abdominal muscles by Floyd and Silver (1950), Campbell and Green (1955) and Ono (1958). The first investigators appear to have proved that the activity is greatest in the internal oblique to provide the protection that the muscle affords to the inguinal canal in the upright posture (see p. 272). Carlsöö (1964) reported that carrying a load on the back always increases activity in rectus abdominis, but carrying one in front of the thighs left rectus abdominis completely silent.

THORAX. Jones, Beargie and Pauly (1953) were the first to suggest that the intercostal muscles play a part in posture, or, at least, in the maintenance of certain flexed postures and adjustments of position. Certainly worthy of further study is the interesting proposal advanced by Jones and Pauly (1957) that the intercostals have as their chief function the maintenance of a proper distance between the ribs while the rib cage is actively elevated by the neck muscles during inspiration (see p. 289). Credence in their theory is strengthened by the independent work of Campbell (1955) who has recorded activity in the scalenes and sternomastoid muscles during quiet respiration and that of Koepke et al. (1958). Surprisingly, these seemingly fundamental problems have not been attacked with any vigour by other investigators (see also p. 288).

MANDIBLE. Moyers (1950), Carlsöö (1952) and MacDougall and Andrew (1953) claimed that the muscles of the jaw which act against gravity in maintaining posture are all those that raise the mandible. Latif (1957), however, while working in our laboratory, demonstrated that temporalis alone is responsible for keeping the teeth in apposition and is constantly active in the upright posture. During the resting, mouth-closed position, there is strikingly greater activity in the posterior fibres which run almost horizontally backwards than there is in the anterior fibres which run vertically. Temporalis is discussed further in Chapter 17.

Posture of Upper Limb

Posture in the upper limb is chiefly a matter of maintaining the integrity of the series of joints in the hanging position. However, in the recumbent posture, if the upper limb is raised to a vertical position, many of the factors which normally govern the posture of the erect whole body come into play for the first time in the upper limb. In the standing position, on the other hand, the hanging limb poses different problems in posture because the force of gravity produces tensions rather than pressures. These tensions are easily carried by the bones which are rigid, but the logical question is often asked: what prevents dislocation of the series of joints? As we have seen already, the most frequent answer—that it is muscular action—is not correct.

SHOULDER. Not surprisingly, low grade postural activity occurs in the upper fibres of trapezius in supporting the shoulder girdle. I have made this observation incidental to other studies in normal subjects over a number of years. Minimal postural activity in the serratus anterior has also been described by Catton and Gray (1951) and confirmed by my own scattered observations during clinical electromyograms.

At the shoulder joint, we have found that the main muscular activity in resisting downward dislocation occurs in supraspinatus (and to a slight extent in the posterior, horizontal-running fibres of deltoid) (Basmajian and Bazant, 1959). The bulk of the deltoid,

and the biceps and triceps show no activity in spite of their
vertical direction. Surprisingly, this is true even when heavy
weights are suspended from the arm. The function of supra-
spinatus is apparently associated with a previously undescribed
locking mechanism dependent upon the slope of the glenoid fossa.
The horizontal pull of the muscle, along with an extreme tighten-
ing of the superior part of the capsule only when the arm hangs
vertically, prevents downward subluxation of the humeral head
(see page 168).

ELBOW. At the elbow joint, without an added load, there is no
activity in the muscles, suggesting that the ligaments carry the
weight (Basmajian and Latif, 1957; Basmajian and Travill, 1961).
The addition of a small or moderate load does not produce any
activity in biceps, triceps, brachioradialis or pronator teres. Per-
haps it is superfluous to note that in flexed positions of the elbow,
the maintenance of the flexed posture is shared by the brachialis
and biceps muscles. However, brachioradialis shows little if any
activity in maintaining flexed postures even against added loads
because, as I have shown before, it is an excellent example of a
"shunt" muscle, as first postulated by MacConaill (1946)—see
p. 123.

WRIST. At the wrist and hand, a minimum of activity is required
to overcome the ordinary force of gravity. Repeated electro-
myograms have revealed a general silence of the forearm and
hand while hanging at rest. The "postural" activity of the wrist
flexors and extensors which accompany the making of a fist or
the grasping of a handle is perhaps more properly a "synergistic"
function and possibly outside the limits of our subject. In this
regard, the only significant postural electromyography of this
region was reported by Dempster and Finerty (1947). They loaded
the hand of the horizontally held forearm and recorded the
activity in various muscles that cross the wrist. When a muscle
was in a superior position and working to support the load against
gravity, its activity was three to four times as great as when it
was below and maximally aided by gravity, i.e., when it was
serving a stabilizing or synergistic function only (see also p. 89).

Recumbent Posture

In conclusion, let us return to the recumbent posture. Here, in this pleasantest of postures, the force of gravity is counteracted by mechanisms that are entirely passive. Repeated electromyograms by many investigators have demonstrated beyond the shadow of a doubt that resting muscles exhibit no neuromuscular activity (Basmajian, 1955a). It is time, then, that all anatomists and physiologists awoke to this fact and so altered their teaching. Contrary to widespread belief, there is no random activity of motor units in a resting muscle to provide what is often hazily called *muscular tone* (see section on Tone on p. 71).

The Upper Limb

M ANY scattered emg studies of the upper limb followed upon the original work in California of Inman, Saunders and Abbott reported in 1944. This chapter will bring together most of the available information in an organized form and deal with the actions of groups of muscles topographically. The wrist, hand and fingers will be dealt with in the next chapter.

Trapezius

Following the classical study of the above authors whose chief concern was with the dynamics of the shoulder (see below), Yamshon and Bierman (1948) and Wiedenbauer and Mortensen (1952) made emg studies of various parts of the trapezius during voluntary movements in a series of normal adults. The trapezius was found to be considerably active during elevation or retraction of the shoulder and during flexion or abduction of the upper extremity through a range of 180°. During scapular elevation the greatest activity was recorded, as would be expected, from the upper parts of the muscle; during retraction, from the middle and lower parts; and during flexion, from the lower half. The

greatest activity in trapezius appears during abduction of the limb and chiefly in the lower two-thirds of the muscle. These findings were confirmation of the California studies and have been confirmed in detail by Thom (1965) of Heidelberg, and in general in our laboratory. I cannot, however, find confirmation for Duchenne's belief that trapezius is a respiratory muscle.

In his study of static loading, Bearn (1961b) discovered that the upper fibres of trapezius, contrary to the universal teaching, "play no active part in the support of the shoulder girdle in the relaxed upright posture." This was confirmed by Fernandez-Ballesteros *et al.* (1964). Some of Bearn's subjects initially showed a low level of activity in this part of the trapezius; but upon their being instructed to relax, the activity stopped entirely. As he notes, this observation is surprising. Indeed, the upper part of the muscle shows through the skin in thin people and appears to be under some tension even when no weight is borne by the limb.

When a load of 10 lbs is held in the hand, fully three-quarters of Bearn's subjects were able to relax the trapezius either immediately or within two minutes. The remainder showed very little activity compared with the result of slight shrugging movements. With a 25-lb load, a third of the subjects could support the weight without emg activity in trapezius. Bearn cautions against the interpretation that this is a desirable way to carry loads: moreover, he ascribes various abnormalities to the habitual depression of the clavicle.

Pectoral Muscles

Inman, Saunders and Abbott (1944) were the first to examine pectoralis major electromyographically. In abduction of the arm, no part of this muscle is active. In forward flexion, the clavicular head is the active part, reaching its maximum activity at 115° of flexion; the sternocostal head remains inactive. With the exception of the recent studies by Ravaglia (1958) in Italy and Scheving and Pauly (1959) in Chicago, the pectoral muscles seem to have been otherwise ignored. Ravaglia was concerned with their alleged accessory functions in respiration. He demonstrated the presence

of moderate activity in them during forced inspiration but none with quiet breathing. Scheving and Pauly confirmed many of the findings of Inman *et al.*, and further confirmed the standard teaching regarding the important activity of the sternocostal head in adduction. However, they found that medial rotation must be against resistance for the pectoralis major to be called into action.

Serratus Anterior

Though serratus anterior must be considered further under "Scapular Rotation," we should note the work of Catton and Gray (1951) who proved beyond a question of a doubt that this is not an accessory respiratory muscle. Their EMG's failed to demonstrate any activity in serratus anterior during voluntary deep breathing, during breathing that was obstructed by forcing the subject to breath through a narrow tube, and even during coughing. The final blow to the concept of this being an accessory respiratory muscle was struck recently by Jefferson *et al.* (1960) who demonstrated that action potentials were generally absent during respiration in the nerve to serratus anterior.

Scapular Rotation

Just as scapular rotation is a distinct and important function, well-known since Duchenne, so the muscles which produce the movement are a distinct functional group. The emg studies of Inman *et al.* first drew special attention to them. As they showed, the upper part of trapezius, the levator scapulae and the upper digits of serratus anterior constitute a unit whose main activities are in concert: they passively support the scapula (slight continuous activity), elevate it (increasing activity) and act as the upper component of a force couple that rotates the scapula (fig. 78).

The lower part of trapezius and lower half or more of the serratus anterior constitute the lower component of the scapular rotatory force couple; they were found to act with increasing vigour throughout elevation of the arm. The lower part of trape-
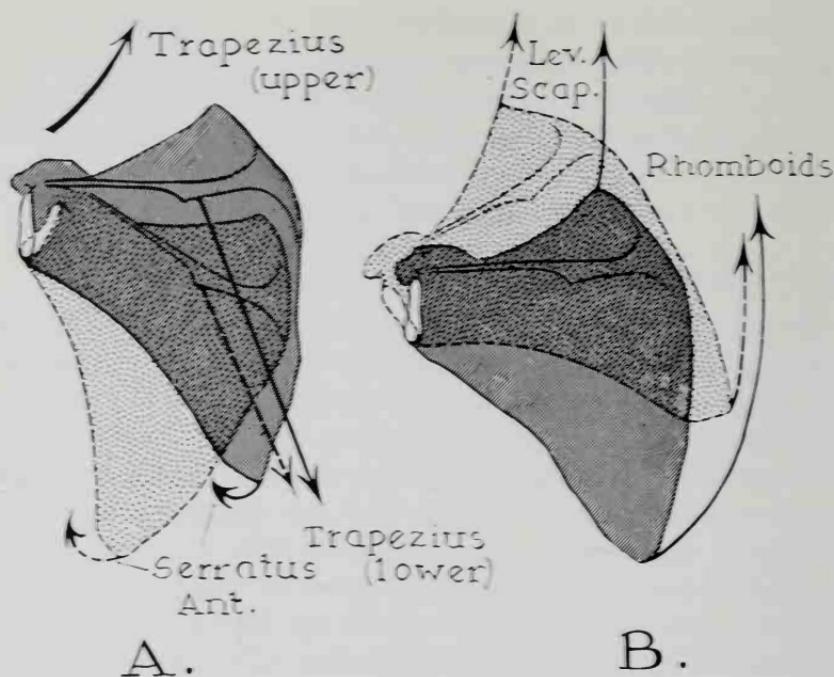
Fig. 78. Scapular rotation and force couples. *A*, glenoid "up;" *B*, glenoid "down." (From Basmajian, 1955a.)

zius is the more active component of the lower force couple during abduction; but in flexion it is less active than serratus anterior apparently because the scapula must be pulled forward during flexion.

The middle fibres of trapezius are most active in abduction especially as the arm reaches the horizontal plane (90°). In forward flexion, the activity of the middle fibres of trapezius decreases during the early range but builds up toward the end. In general, then, the middle trapezius serves to fix the scapula but must relax to allow the scapula to slide forward during the early part of flexion.

The rhomboid muscles (major and minor) imitate the middle trapezius, being most active in abduction and least during early flexion.

Movements and Muscles of the Glenohumeral Joint

The chief muscles that act upon the shoulder (glenohumeral) joint are the deltoid, the pectorales (discussed above), the latissimus dorsi, teres major, and the four rotator cuff muscles—subscapularis, supraspinatus, infraspinatus and teres minor. The considerable interest these muscles have aroused amongst electromyographers is not surprising, for the movements and protection of the shoulder joint are of paramount importance. Below are the composite results derived from the work of various authors.

ABDUCTION. The activity in the deltoid increases progressively and becomes greatest between 90° and 180° of elevation (fig. 79). The activity of supraspinatus increases progressively, too (Inman et al.). Thus, it is not simply an initiator of abduction as was
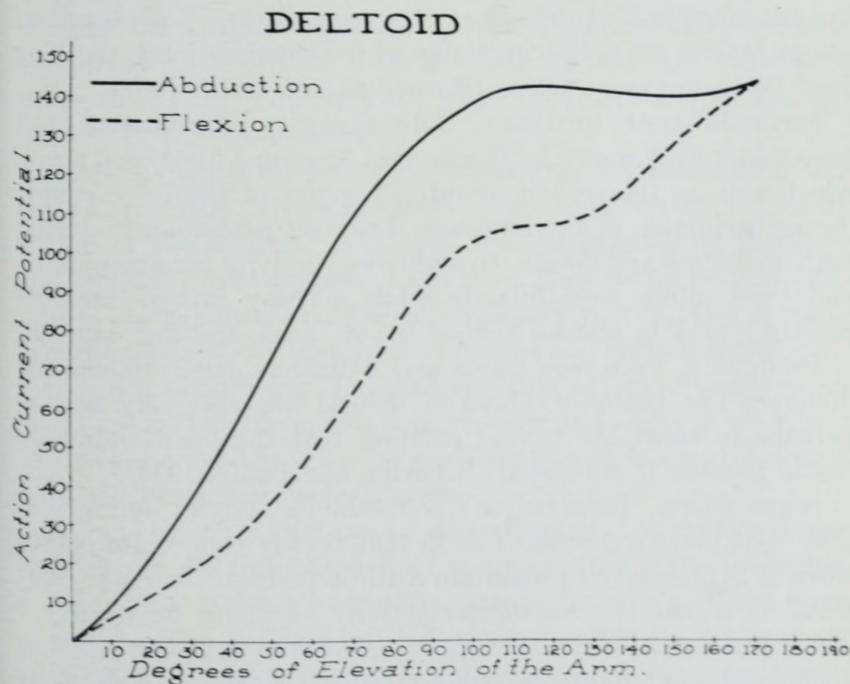
FIG. 79. Relation of emg activity in deltoid (in arbitrary units) to degree of elevation of arm. (From Inman, Saunders and Abbott, 1944.)

formerly taught. Our own studies have conclusively substantiated
these statements as have those of Wertheimer and Ferraz (1958).
Quite surprising but rational is the discovery by Van Linge and
Mulder (1963) that complete experimental paralysis of supra-
spinatus in man simply reduces the force of abduction and power
of endurance. They concluded that in abduction supraspinatus
plays only a quantitative and not a specialized role. No part of
pectoralis major is active during abduction. The rôle of biceps
brachii in abduction seems to be confined to a contribution in
maintaining this position while the arm is laterally rotated and
the forearm supine. When the arm is medially rotated and the
forearm prone, biceps does not contribute to abduction (Bas-
majian and Latif, 1957).

FLEXION. The clavicular head of pectoralis major along with
the anterior fibres of deltoid are the chief flexors. Both heads of
biceps brachii are active in flexion of the shoulder joint, the long
head being the more active (Basmajian and Latif, 1957).

DEPRESSORS OF HUMERUS. Subscapularis, infraspinatus and
teres minor were shown by Inman *et al.* to form a functional group
which acts as the second or inferior group of the force couple
during abduction of the humerus. They act continuously during
both abduction and flexion. In abduction, activity in infraspinatus
and teres minor rises linearly while activity in subscapularis
reaches a peak or plateau beyond the 90° angle and then falls off.

ADDUCTION. Pectoralis major and latissimus dorsi produce ad-
duction. The posterior fibres of deltoid are also very active,
perhaps to resist the medial rotation that the main adductors
would produce if unresisted (Scheving and Pauly, 1959).

TERES MAJOR. Teres major never exhibits activity during mo-
tion "but plays a peculiar rôle in that it only comes into action
when it is necessary to maintain a static position. In static posi-
tions, it reaches its maximum activity at about 90 degrees."
These statements of Inman and his colleagues have been neither
challenged nor confirmed until recently. Kamon (1966) finds
that teres major is very active in movements of the free arm
during gymnastics on the pommeled horse. On the other hand,

even during the vigorous activity of shot-putting, the teres major remains relatively quiet (Hermann, 1962).

LATISSIMUS DORSI. Medial rotation of the humerus is performed by this muscle which is more important than pectoralis major according to Scheving and Pauly (1959) who found the latter muscle only active with resisted rotation.

DELTOID. The above authors found that the three parts of deltoid are active in all movements of the arm, as did Yamshon and Bierman in an earlier and less sophisticated study (1949). In flexion and medial rotation, the anterior part is more active than the posterior; in extension and lateral rotation, the posterior is the more active; and in abduction the middle part is the most active. Scheving and Pauly suggest that, although one part of deltoid may act as the prime mover, the other parts contract to stabilize the joint in the glenoid cavity. They further recommend the inclusion of deltoid with the four rotator cuff muscles as stabilizers of the joint, but our work (reported below) does not endorse their recommendations.

Recently in Brazil, Wertheimer and Ferraz (1958) found that the anterior part of deltoid shows its principle action in forward flexion of the shoulder joint, but also participates in elevation and (slightly) in abduction of the arm. They found no participation in medial rotation. The intermediate portion acts strongly in abduction and elevation of the arm and also participates slightly in flexion and extension. The posterior part has its principal action in extension, but the action is inconstant and slight in abduction and elevation of the arm. Its participation in lateral rotation is minimal, being practically absent.

Hermann (1962), in a careful emg study of shot-putting, found that ideally the anterior deltoid is active during the entire manoeuvre. The greatest contracting occurs during the thrust phase of the shoulder and arm but before the shot is released from the hand. The middle fibres come into play—and into very strong action—after the thrust is initiated. The posterior fibres play no important rôle until the moment just as the shot leaves the hand.

Prevention of Downward Dislocation of the Humerus

The part played by various muscles during movements of the shoulder joint has been the subject of investigation and argument for more than a century. Even though most of the important questions on movements in the shoulder area have been answered, little reliable information had been available regarding the rôle of such muscles in *maintaining joint stability*. In particular, the mechanism preventing downward dislocation or subluxation of the shoulder joint has not been adequately explained—indeed, it has been largely ignored. Cotton in 1921 and Fairbank in 1948, considering the matter in connection with fractures of the humeral neck, both assigned the greatest importance to the vertically running scapulohumeral muscles, for example, deltoid and biceps. During some incidental studies of the region, we were surprised to find the exact opposite. Therefore, to clarify the part played by the muscles and the capsule of the joint in preventing downward dislocation of the vertical or adducted humerus, the following two types of systematic investigation were performed (Basmajian and Bazant, 1959): (1) an electromyographic study of the deltoid, supraspinatus, infraspinatus, biceps and triceps of a series of young men, using multiple concentric-needle electrodes; and (2) a study of gross dissections of the shoulder joint.

Our findings do not support the hypothesis advanced by Cotton and endorsed by Fairbank. In fact, they completely disagree. It was apparent from the electromyographic results that the deltoid (the muscle one would expect to be especially active in preventing downward dislocation of the humerus) is inactive even with heavy pulls. Other muscles running vertically from the scapula to the humerus, particularly the biceps and the long head of triceps, are conspicuously inactive as well. Therefore, there now seems to be little, if any, reason to doubt that downward dislocation is prevented by the superior part of the capsule along with the supraspinatus (and to a lesser extent the posterior fibres of the deltoid). Strangely enough, these structures run in a horizontal and not in a vertical direction (fig. 80). Bearn (1961) confirmed the findings (in considerable detail) quite independently and using loads of 25 lbs.
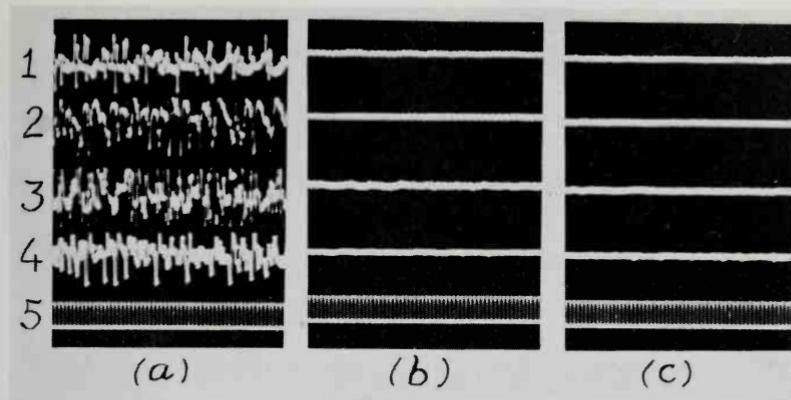
FIG. 80. EMG's, a, during abduction; b, unloaded arm hanging; and c, heavy downward pull applied to arm. Lines 1, 2 and 3—anterior, middle and posterior fibres of deltoid; line 4—supraspinatus; line 5—time marker: 10-msec intervals. (From Basmajian, 1961.)

The mechanism by which these horizontally placed structures succeed is dependent upon a well known, but previously unexplained fact, namely, the obliquity of the glenoid fossa. When the scapula is examined in its correct orientation, invariably it is found to face somewhat upward in addition to forward and laterally (fig. 81). It now appears that this slope of the glenoid fossa—particularly its lower part—plays an important rôle in preventing downward dislocation or subluxation. As the head of the humerus is pulled downward, it is of necessity forced laterally because of the slope of the glenoid fossa (fig. 82). If this lateral movement could be stopped, the result would be a stopping of the downward movement. The superior part of the capsule of the joint and the supraspinatus (as well as the posterior fibres of the deltoid) are so placed that they can—indeed they must—tighten to prevent the downward dislocation (fig. 83). Simple as this explanation may seem, it is dependent on our findings that (1) the vertically placed muscles definitely remain relaxed while (2) the supraspinatus (and posterior deltoid) become quite active and (3) the superior part of the capsule becomes taut. The very
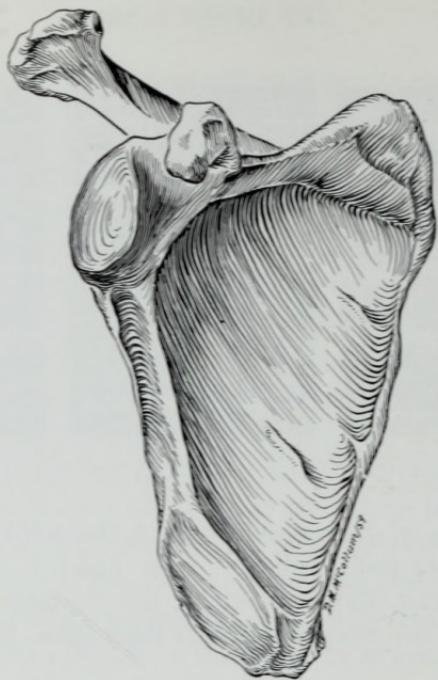
FIG. 81. Correct orientation of the right scapula viewed directly from in front at eye level. (From Basmajian and Bazant, 1959.)
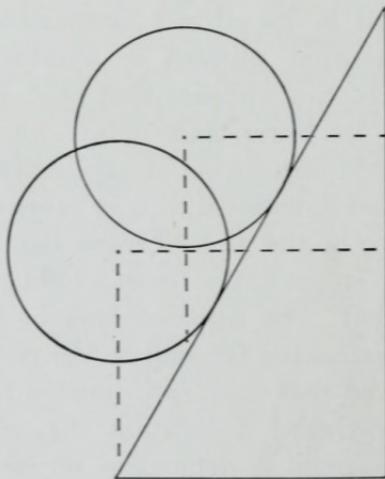
FIG. 82. Diagram to illustrate locking mechanism at shoulder. The farther down the slope the ball slides, the farther laterally it is displaced. If the lateral displacement can be prevented, the ball cannot move downward. (From Basmajian and Bazant, 1959.)
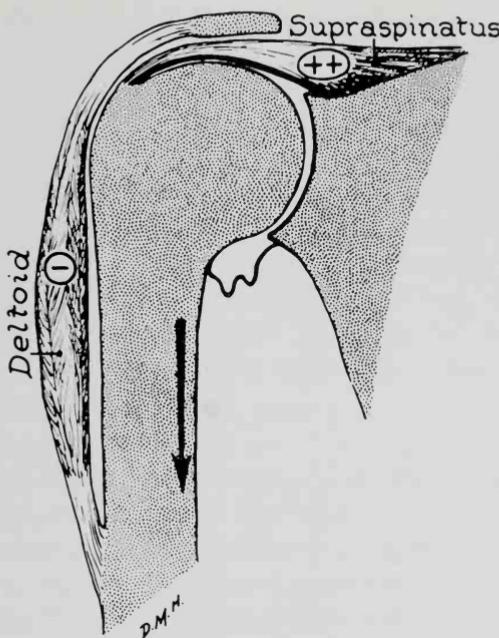
FIG. 83. Diagram contrasting presence of moderate activity in supraspinatus with none in deltoid during loading in the direction of arrow (see text).

rareness of downward dislocation of the normal shoulder joint confirms the effectiveness of this locking mechanism.

The ordinary effect of gravity on the unloaded arm is counteracted in many persons by the superior part of the capsule. In this area the coracohumeral ligament forms a real thickening and apparently this is an important function of the ligament. With moderate or heavy loads, the supraspinatus is called upon to reinforce the horizontal tension of the capsule; in some persons it is required even without a load. The posterior fibres of the deltoid, imitating in general the direction of the supraspinatus, must act in the same way but to a lesser extent.

The above described mechanism cannot operate when there is abduction of the humerus. As a result, the head can be easily subluxated when it is in the abducted position in the cadaver.

Fairbank convincingly demonstrated that subluxation can be also produced in anesthetized normal men, but his roentgenograms of the subluxated shoulders show in each case a real degree of abduction of the humerus in relation to the position of the scapula. It would appear that in these unconscious subjects the subluxation was preceded by a drawing downward of the glenoid fossa (that is, relative abduction of the humerus and thus a neutralization of the locking mechanism). The muscles that prevent dislocation of the joint in its unstable position are the "rotator cuff" muscles—supraspinatus, infraspinatus, teres minor and subscapularis (and perhaps teres major and other muscles spanning the joint).

Elbow Flexors

Although they can be felt quite easily, the biceps brachii, the brachialis and the brachioradialis have not been fully understood as far as their integrated functions are concerned. Furthermore, both Duchenne and Beevor introduced and perpetuated errors that require correction. And again, although it is obvious that these muscles are primarily concerned with flexion, a variety of theories have obscured the rôle played by each during flexion and other movements of the elbow. It is probably fair to say that the few formal studies of these muscles (both with and without objective techniques) have been either too sharply circumscribed in approach or too highly generalized and deductive.

For these reasons, we made a detailed electromyographic study of both heads of the biceps, the brachialis and the brachioradialis in a long series of young adults (Basmajian and Latif, 1957).

A careful consideration of the time-sequence of activity indicated there is a completely random selection in the sequence of appearance and disappearance of activity in these muscles. For example, during slow flexion with the forearm supine, all the muscles that showed any activity began this activity simultaneously in about half of the subjects. However, in only about one-quarter of them did the activity end simultaneously. In a small number in whom the activity did not begin simultaneously, it did, however, end simultaneously.

Any of the muscles that was to show activity during a movement functioned first or last in an unpredictable fashion, i.e., there was no set pattern. In the same way, the activity ceased in the muscles in an unpredictable order. Moreover, the muscle that was to show the greatest activity in individual subjects only occasionally began first and ended last.

Our results provided convincing evidence that in the movements produced by the biceps, the brachialis and the brachioradialis there is a fine interplay between them; this was to be expected. What is more striking, however, is the wide range of response from any one muscle in our series. Thus, although a general trend may be described, there is rarely any unanimity of action. For example, the brachialis is generally markedly active during quick flexion of the supine forearm, but in one of our subjects it was completely inactive.

These findings re-emphasize the general biological principle that there is a range of response in any phenomenon. It would seem that anatomists and clinicians have taken too little heed of this wide range of individual pattern of activity in something even so simple as elbow-flexion.

In our study, the long head of the biceps showed more activity than the short head in the majority of the subjects during slow flexion of the forearm, during supination of the forearm against resistance and during flexion of the shoulder joint (although there was little difference between the activity of the two heads during isometric contraction and during extension of the elbow). Sullivan, Mortensen, Miles and Greene (1950) reported similar findings in a more limited but fine experimental series with surface electrodes during flexion only.

The biceps is generally active during flexion of the supine forearm under all conditions and during flexion of the semiprone forearm when a load (of 2 pounds) is lifted (fig. 84). However, with the forearm prone, in the majority of instances the biceps plays little if any rôle in flexion, in maintenance of elbow flexion and in antagonistic action during extension, even with the load. Beevor (1903, 1904) stated that if the forearm is in supination
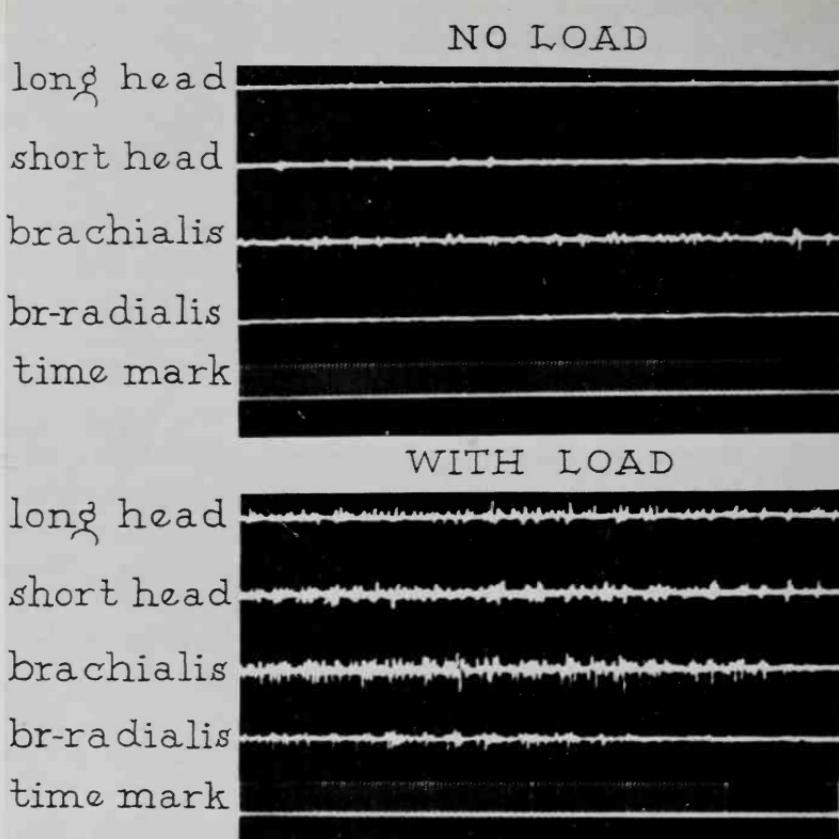
Fig. 84. EMG's of the two heads of biceps, the brachialis and the brachioradialis during slow flexion of semiprone forearm.

the biceps acts during flexion when there is a resistance of as little as 4 ounces, but that in a position of complete pronation it does not act until the resistance is at least 4 pounds. The results of our emg study support Beevor's observations in regard to flexion.

The biceps is usually described as a supinator of the forearm. In our study, no activity in the muscle was demonstrated in the majority of the subjects during supination of the extended forearm through the whole range of movement except when resistance to supination was given. However, activity was observed in all

the subjects when supination was strongly resisted. It follows that, generally, the biceps is not a supinator of the extended forearm unless supination is resisted.

It is necessary to explain why the biceps does not ordinarily supinate the extended forearm. It appears that because of the tendency of the biceps to flex the forearm, it is reflexly inhibited. Thus the extended position of the forearm is maintained while the supinator does the supinating. On the other hand, when supination is resisted, the biceps comes into strong action, and we have noted that usually the previously extended forearm is partly flexed as well during supination against resistance.

The slight action of the biceps in flexion of the shoulder joint which we observed confirms the accepted teachings concerning the action of this muscle at the shoulder. Because of the difficulty in divorcing supination of the forearm from lateral rotation of the humerus, no final conclusions can be drawn in regard to the textbook statement that the long head of biceps is an abductor of the arm. In our study, when the forearm was in the prone position, there was relatively no change in the position of the humerus; yet there was a dramatic disappearance of activity in the biceps. This suggests that the textbook statement is, at best, questionable.

The brachialis has been generally and erroneously considered by anatomists to be a muscle of speed rather than one of power because of its short leverage. We found it to be a flexor of the supine, semiprone and prone forearm in slow or quick flexion, with or without an added weight. McGregor (1950) has correctly described it as a "flexor *par excellence* of the elbow joint." Apparently brachialis is called upon to flex the forearm in all positions because the line of its pull does not change with pronation or supination.

Maintenance of specific flexed postures of the elbow, i.e., isometric contraction, and the movement of slow extension when the flexors must act as anti-gravity muscles both generally bring the brachialis into activity in all positions of the forearm. This is not the case with the other two flexor muscles. Thus, the brachialis

may also be designated the "workhorse" among the flexor muscles of the elbow.

A short burst of activity is generally seen in all the muscles during quick extension. This activity can hardly be considered antagonistic in the usual sense. Rather, it may provide a protective function for the joint. Biceps is particularly active during quick extension with an added load.

In the past, the brachioradialis has been described as a flexor, acting to its best advantage in the semiprone position of the forearm. We found in most subjects that the brachioradialis does not play any appreciable rôle during maintenance of elbow flexion and during slow flexion and extension when the movement is carried out without a weight. When a weight is lifted during flexion, the brachioradialis is generally moderately active in the semiprone or prone position of the forearm and is slightly active in the supine position. There is no comparable increase in activity with the addition of weight during maintenance of flexion and during slow extension. We also found that in most instances the brachioradialis is quite active in all three positions of the forearm during quick flexion and extension. It follows that the muscle is a reserve for occasions when speedy movement is required and when weight is to be lifted, especially in the semiprone and the prone positions. In the latter position, the biceps usually does not come into prominent action. Furthermore, the activity of the brachioradialis in speedy movements is related to its function as a shunt muscle (see p. 123).

The brachioradialis has been described since Duchenne's day as a supinator of the prone forearm and a pronator of the supine forearm acting to the semiprone position in both cases. Our study showed that it neither supinates nor pronates the extended forearm unless these movements are performed against resistance. Here, at most, brachioradialis acts only as an accessory muscle, coming into action when strength is required to supinate or to pronate the forearm. More probably, it acts only as a synergist.

Our observations strongly suggest that the biceps, the brachialis and the brachioradialis differ in their flexor activity in the

three positions of the forearm (prone, semiprone and supine). However, all three muscles act maximally when a weight is lifted during flexion of the semiprone forearm. The semiprone position of the forearm has been described as the natural position of the forearm, the position of rest and the position of greatest advantage for most functions of the upper limb (Basmajian, 1955a).

PRONATOR TERES AND ELBOW FLEXION. Our investigations have shown that pronator teres contributes to elbow flexion only when resistance is offered to the movement (Basmajian and Travill, 1961). It shows no activity during unresisted flexion whether the forearm is prone, semiprone or supine (see fig. 87 on p. 180).

Before leaving the flexor muscles of the elbow, we might note that Wells and Morehouse (1950) believe that biceps and triceps (and latissimus dorsi) act as cocontractors in exerting a pull such as on an aircraft control stick. They found that the extent of the "contribution" each muscle makes is altered when the position of the arm is changed (see p. 89). When the arm is pulling in an extended position, the biceps dominates the action, but in the flexed or intermediate position, triceps is brought strongly into action. These findings can hardly be valid evidence of cocontraction because of many complicating factors in the set-up. However, Wells and Morehouse did show that, as far as muscular dynamics is concerned, "the best arm position of a pilot seated in a conventional upright position and operating a control stick is one which is intermediate between flexion and extension."

Triceps Brachii

My colleague, Anthony Travill (1962) has found that the long head of triceps is surprisingly quiescent during active extension of the elbow regardless of the position of either the subject or his limb. The medial head, however, is always active and appears to be the prime extensor of the elbow; meanwhile, the lateral head shows some activity as well. Against resistance, the lateral and long heads are recruited. Therefore, we might compare the medial head of triceps to the brachialis which we noted above to be the workhorse of the elbow flexors; it is the workhorse of the ex-

tensors. The lateral and long heads are reserves for extension just as the two heads of biceps are reserves for flexion.

Travill confirmed Duchenne's view that, of the two superficial heads, the long head is the less powerful during extension. This is probably due to the lack of fixation of the scapular origin and the necessity of adducting the shoulder with the forearm either flexed or extended. Too strong a contribution from the long head would tend to give extension during adduction of the arm.

Pronation and Supination of Forearm

PRONATORS. Until recently no accurate authoritative information existed on the relative functional rôles of the two pronator muscles, although their gross anatomy is adequately described in the standard textbooks. Our investigation of the pronator teres and the pronator quadratus in a series of volunteers revealed that the few remarks on function that are presently available in books are largely misleading (Basmajian and Travill, 1961).

In each subject three groups of records were made from needle electrodes (fig. 85). In the first group, the elbow was kept in the extended, fully supported position on the table top (fig. 86, α).
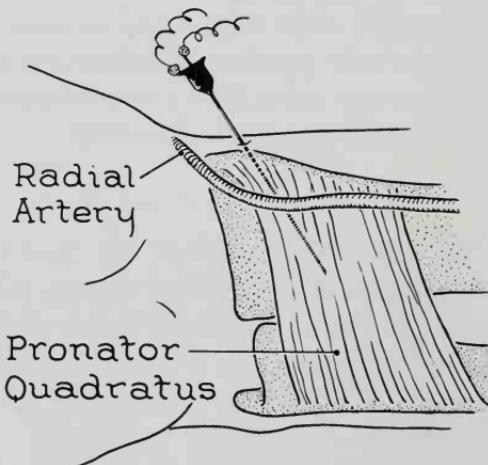
FIG. 85. Diagram of electrode placement in pronator quadratus. (From Basmajian and Travill, 1961.)
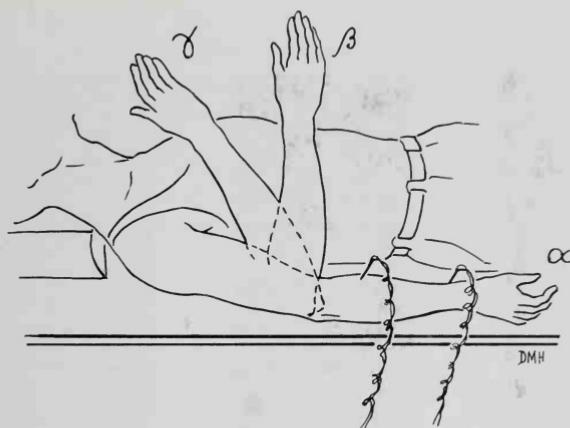
Fig. 86. Diagram of primary positions of limb during three groups of tests (see text). (From Basmajian and Travill, 1961.)

In the second group, the elbow was flexed to a right angle, with the forearm vertical and the arm and elbow supported (fig. 86, β) In the third group, the elbow was flexed to an acute angle while it was still fully supported (fig. 86, γ). In each of these three groups of tests, records from the two muscles were made during the following movements and positions: (1) slow pronation from the comfortable supine position to the fully prone position, (2) fast pronation through the above range, (3) "hold" in the fully prone position, (4) slow supination through the whole range to full (forced) supination, and (5) fast supination through the above range.

Both pronator quadratus and pronator teres are active during pronation, the consistent prime pronating muscle being the pronator quadratus (fig. 87). This is true irrespective of the positions of the forearm in space or the angulation of the elbow joint. In general, the pronator teres is called in as a reinforcing pronator whenever the action of pronation is rapid. Similar reinforcement occurs during pronation against resistance.

Whether pronation is fast or slow, the activity in the pronator quadratus is markedly greater than that in the pronator teres. This observation conflicts with the opinions offered in a number
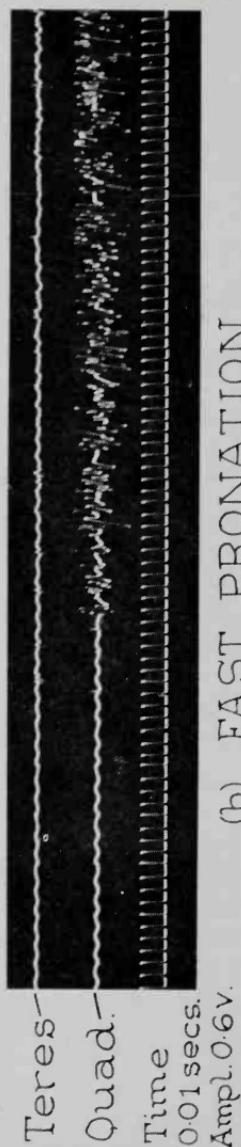
Fig. 87. Typical EMG's of *a*, slow pronation; *b*, fast pronation; and *c*, slow flexion of elbow. (From Basmajian and Travill, 1961.)

of the internationally recognized textbooks (Steindler, 1955; Johnston, Davies and Davies, 1958; Hamilton and Appleton, 1956; Lockhart, Hamilton and Fyfe, 1959). Of the North American textbooks (e.g., *Gray's Anatomy* edited by Goss, 1959), almost all sit squarely on the fence and suggest that both muscles pronate without preference. Only two of them firmly indicate that the pronator quadratus is the main pronator (Hollinshead, 1958; Basmajian, 1960).

A number of authors have likewise expressed the view that the pronator teres displays its greatest activity either during mid-flexion of the elbow (Steindler, 1955; Lockhart, 1951) or during full extension (Hamilton and Appleton, 1956; Hollinshead, 1958). However, we were surprised to find that, regardless of whether the pronating action is carried out swiftly or slowly, the angle of the elbow joint has no bearing on the amount of activity of the pronator teres.

During slow supination there is no activity whatsoever in either of the pronators—though some have suggested that the deeper layer of the pronator quadratus acts as a supinator. De Sousa *et al.* (1957, 1958), using a different approach, have independently arrived at the same conclusion.

During fast supination, there is negligible activity in the pronators. This is rather surprising in view of earlier work, mentioned above, on the electromyographic activity of the biceps and triceps during flexion and extension of the elbow (Barnett and Harding, 1955; Basmajian and Latif, 1957). In those muscles, a sharp burst of antagonistic activity occurs during fast movements, this activity being thought to be the manifestation of a protective stretch reflex.

De Sousa and his colleagues (1957, 1958, 1961) in São Paulo, Brazil, showed that pronator quadratus is a pronator only. They agree with us that it participates in normal pronation, but there is some difficulty in reconciling with our own experience their finding that there is little early activity in pronator quadratus during the early stages of pronation. Their explanation of the difficulty, which indeed seems to be a valid one, is that at the

beginning of unresisted pronation the natural elastic recoil from complete supination is quite enough. Our "pronations" were begun from the comfortably supine, not the fully supine, position. In any case, pronator teres acted no earlier than quadratus in their series. Moreover, the flexor carpi radialis, brachioradialis and extensor carpi ulnaris were shown to have no pronating function.

SUPINATORS. Supination of the forearm in man is undeniably of fundamental importance and yet, all too often, the parts played by the chief supinator muscles are either ignored or taken for granted. Throughout the textbooks, there is no thread of consistency and the truth appears to be so tangled with hopeful guesses it cannot be recognized. For example, only in recent years did we confirm Beevor's strong insistence in 1903 that brachioradialis (known for years as "supinator longus") is not a true supinator (see p. 176).

Recently, we carried out an electromyographic study of the supinator and the biceps brachii in a series of young volunteers (Travill and Basmajian, 1961). This study was complementary to and, in part, overlapped by that on the pronator muscles outlined above. A needle electrode was inserted into the middle of each of the following four muscles: the supinator, the biceps brachii, the pronator quadratus and the pronator teres, the pronators being tested simultaneously as controls only.

Two series of recordings were made from each subject: the first series with the elbow extended, and the second with the elbow flexed to 90°. With each of these two positions recordings were made during: (1) the movement of supination from full pronation, (2) the "hold" position of maximum supination and, finally, (3) the return movement of pronation to the original comfortably supine position. Recordings were made during slow movements, fast movements and forceful movements against the resistance offered by the grip of an observer.

Slow unresisted supination, whatever the position of the forearm, is brought about by the independent action of the supinator (fig. 88). Similarly, fast supination in the extended position re-
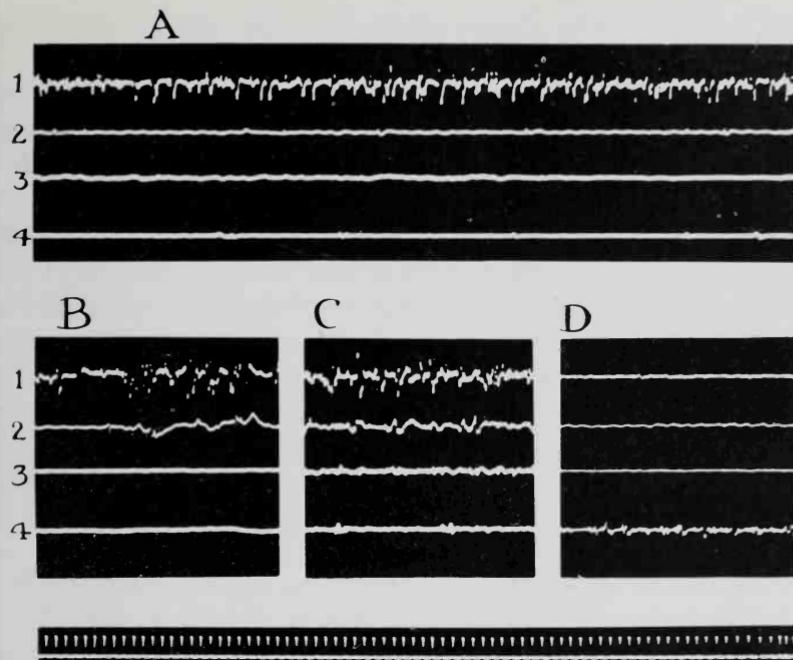
FIG. 88. EMG's during *A*, slow supination; *B*, fast supination; *C*, forceful supination against resistance; and *D*, pronation of the forearm. Channel *1*, supinator; *2*, biceps brachii; *3*, pronator teres; and *4*, pronator quadratus. Time marker: 10-msec intervals. (From Travill and Basmajian, 1961.)

quires only the supinator; but fast unresisted supination with the elbow flexed is assisted by the action of the biceps. All movements of forceful supination against resistance require the cooperation of the biceps in varying degrees.

This last-mentioned cooperative activity of the supinator and the biceps during resisted supination, especially when the elbow is flexed, has never been seriously questioned in the past. Primacy of the supinator during the unresisted movement has not, however, received such universal acceptance, even though it was first suggested by Duchenne and broadly hinted at by Bierman and Yamshon (1948). For example, Steindler (1955) and Gardner,

Gray and O'Rahilly (1960) emphasize only the power of the biceps against resistance; this power is undeniable.

During supination, the action of supinator is augmented by that of the biceps. This was similar to our earlier findings for pronation, where pronator quadratus is augmented by the pronator teres when required.

Both the supinator muscles are completely relaxed during pronation (slow, fast or resisted). This is again similar to our findings for pronation, where complete relaxation of the pronator quadratus and the pronator teres during supination is the rule.

The "hold" or static position of supination depends on activity in supinator for the maintenance of the supine posture. Against added resistance, however, the biceps always becomes active. The movement of supination is initiated, and mostly maintained, by the supinator; it is only assisted by the biceps as needed to overcome added resistance.

ANCONEUS. This small muscle has been the subject of controversy since Duchenne suggested a special rôle for it, that of abduction of the ulna during pronation of the forearm. Though not conclusive, my scattered emg studies of this muscle appear to confirm Duchenne's suggestion. On the other hand, one never sees cases of localized paralysis of anconeus from which its rôle as an abductor could be confirmed. Furthermore, pronation is equally efficient with or without abduction. However, some simple observations reveal that the usual way in which most persons carry out pronation includes the slight abduction of the ulna. Thus the hand can be "turned over" without its shifting away from its original position. The anconeus is in the ideal position to perform this secondary movement.

Under the direction of Prof. de Sousa of São Paulo, Brazil, Da Hora (1959) of the University of Recife reinvestigated anconeus morphologically and electromyographically. From the latter study he concluded that anconeus was always active during extension of the elbow. What is surprising, however, is his finding that it is active in both pronation and supination whether these movements are resisted or unresisted. He also reported activity during flexion

of the elbow, especially against resistance. These bizarre findings cannot be accepted without question or confirmation. Indeed, a legitimate interpretation of Da Hora's electrode technique suggests that his "pick-up" was not sufficiently localizing.

Ray, Johnson and Jameson (1951) reported that anconeus was very active during the whole of pronation. However, Travill (1962) concluded from his definitive emg study of this muscle that it is only active when resistance is offered to the movement— but it is quite as active during resisted supination. All authors confirm the classical view that anconeus is most active during extension of the elbow.
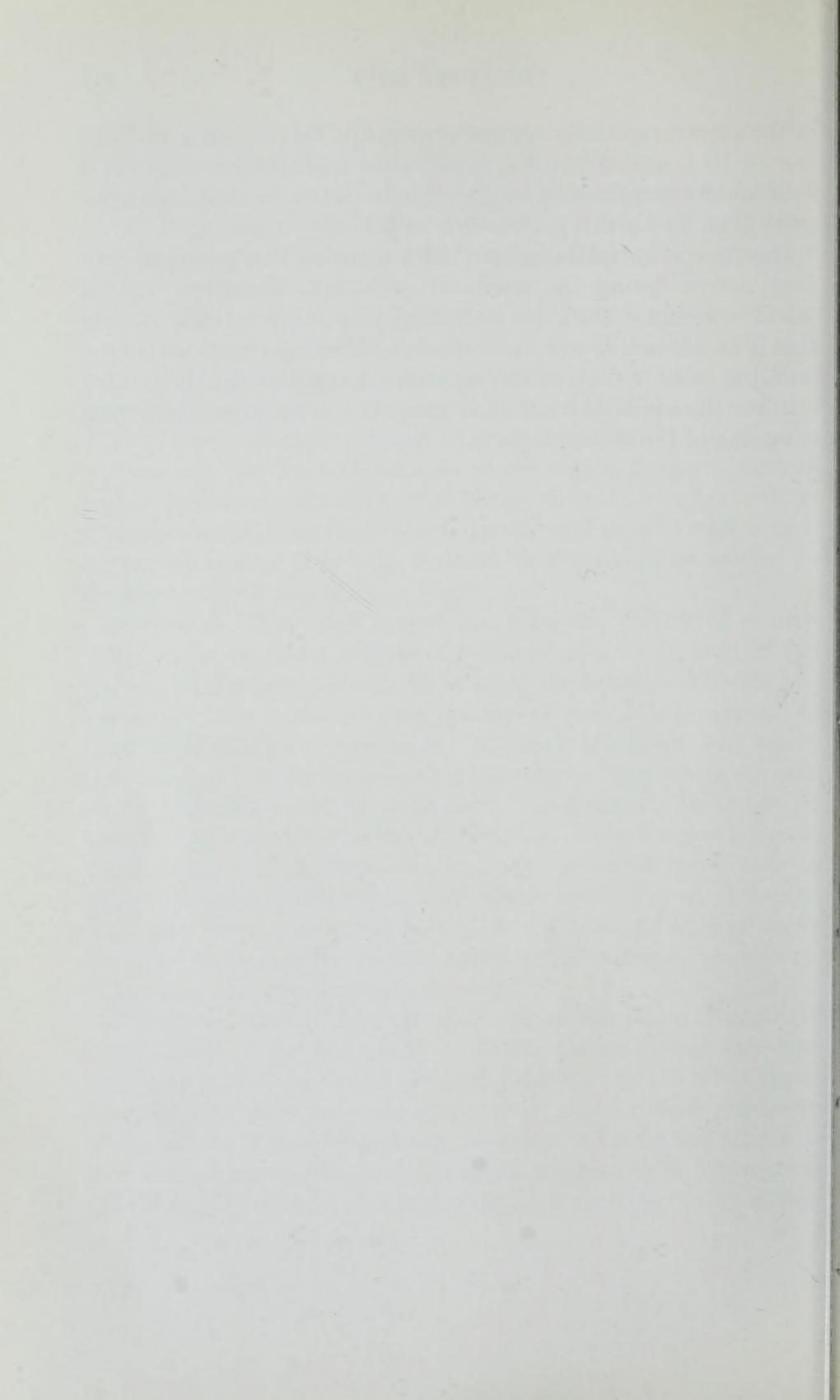
Wrist, Hand, and Fingers

THE two radial extensors of the wrist have been the special subject of electromyographic examination by Tournay and Paillard (1953). They showed that during pure extension of the wrist the extensor carpi radialis brevis is much more active than the longus whether the movement is slow or fast. Actually, except with fast extension, the longus was essentially inactive. However, the rôles of the two muscles are completely reversed during prehension or fist-making; now the longus is very active as a synergist. This appears to be an extremely important observation. The two muscles are both quite active during abduction of the wrist, as one would guess from their positions.

The work of Gellhorn (1947) and of Dempster and Finerty has already been described in Chapter 4 (p. 89).

Bäckdahl and Carlsöö (1961) found that during extension of the wrist there is a reciprocal innervation between extensors and flexors. Extensores carpi radiales (longus et brevis) and extensor carpi ulnaris, as well as the extensor digitorum, work synchronously; none seems to be the prime mover. This was confirmed by McFarland et al. (1962). During forced extreme flexion of the wrist, there is a reactive cocontraction of the extensor carpi

ulnaris, apparently to stabilize the wrist joint; this does not occur with the extensor digitorum and extensores carpi radiales.

During flexion of the wrist, the flexores carpi radiales, ulnaris and digitorum superficialis act synchronously, according to Bäck- dahl and Carlsöö—none is the prime mover. Flexor digitorum profundus plays no rôle. Two possible muscles in the antagonist position (the radial extensors of the wrist and the extensors of the fingers) are passive, even in extreme flexion of the wrist; but the extensor carpi ulnaris shows marked activity as an antagonist.

In abduction and adduction, the appropriate flexors and ex- tensors act reciprocally as one might expect, the antagonist mus- cles relaxing. Extensor digitorum contracts during abduction (radial abduction), but Bäckdahl and Carlsöö found that this contraction is not limited to the radial part of the muscle. Ap- parently this last activity has a synergistic function. McFarland *et al.* also found activity in extensor digitorum during extremes of abduction and adduction of the wrist; moreover, the flexor digi- torum superficialis was active too. This group of investigators also emphasize the uniform occurrence of antagonist activity in the flexors when the wrist is extended and the metacarpophalangeal joints hyperextended.

Fingers

Several studies of the movements of the fingers have been reported in the past decade. For example, Person and Roshtchina (1958) of Moscow were concerned with the nervous mechanisms that enable a person to perform isolated movements of a single finger. They studied the common flexors and extensors of the fingers during rhythmic flexions and extensions. When all the fingers are moving simultaneously the activity of the "antagonist" muscles conforms to the principle of reciprocal inhibition (p. 86). When only the little finger or ring finger is moving while the others are extended, the extensor is active during both extension and flexion. When one finger is moved while the others are kept bent, the flexor is active during both movements.

If a single finger moves, the "antagonist" must remain active to immobilize the other fingers. However, if the other fingers are

held immobile by an observer, there is no activity in the antagonist muscle.

Backhouse and Catton (1954) studied the lumbricals of the hand and proved conclusively that they are only important in extension of the interphalangeal joints reinforcing the action of the extensor digitorum and interossei. They agree in large measure with the Australian anatomist, Sunderland (1945), who suggested that the importance of lumbrical-interosseus extension at the interphalangeal joints is in the prevention of hyperextension of the proximal phalanx by the extensor digitorum. This preventive action allows a more efficient pull on the dorsal expansion which extends the interphalangeal joints (figs. 89 to 91).

Metacarpophalangeal flexion is performed by a lumbrical only when the interphalangeal joints are extended. Backhouse and Catton concluded that a lumbrical has no effect on rotation or radial deviation of its finger during opposition with the thumb (as first suggested by Braithwaite, Channell, Moore and Whillis, 1948, in their classic morphological study).

At Washington University in St. Louis, Lake (1954, 1957) made a simultaneous study of the extensor digitorum (communis), flexor digitorum superficialis (or sublimis) and the second and third dorsal interossei. She found that the extensor digitorum begins or increases its activity with the inception of interphalangeal (IP) joint extension regardless of the position of the metacarpophalangeal (MP) joints. During extension or hyperextension of the MP joint, extensor digitorum alone was active.

Flexor digitorum superficialis is active during flexion of the middle phalanx (proximal IP joint), and it is active in flexion of the MP joint providing the next distal joint is stabilized. Surprisingly, the superficialis is active during rapid, forceful IP extension regardless of the position of the MP joint.

The interossei in Lake's research were found to be markedly active from the very onset of flexion of the MP joint even with moderate effort. IP joint position was of no consequence in this. The interossei also showed activity before the onset of visible extension in either the proximal or distal IP joint. In the case of ex-

Hand relaxed in semi-flexion

⌞___⌟ ⅕ sec.   [500 μV.

Hand in firm extension at all joints

Firm flexion of metacarpo-phal-
angeal joints and extension of
interphalangeal joints
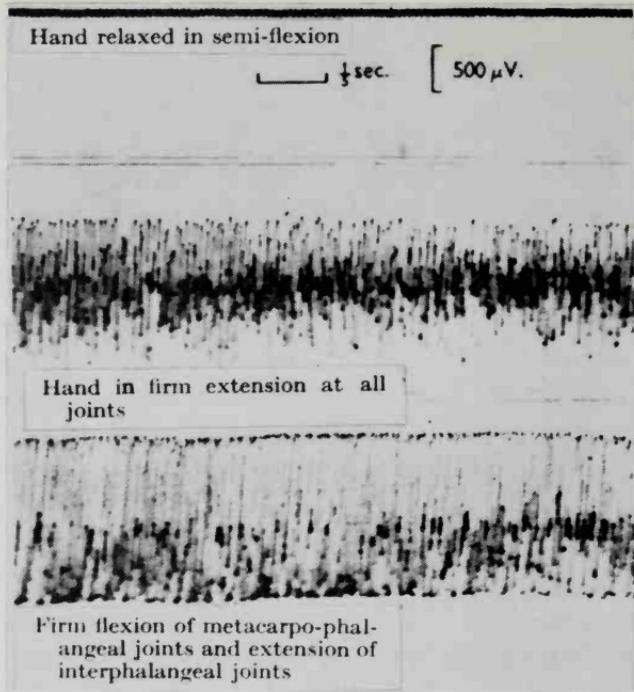
Fig. 89. EMG's of a lumbrical muscle in several positions of the hand. (From Backhouse and Catton, 1954.)

[250 μV.

Forced opposition against thumb in extension
compared with

Muscle relaxed   Muscle fully active
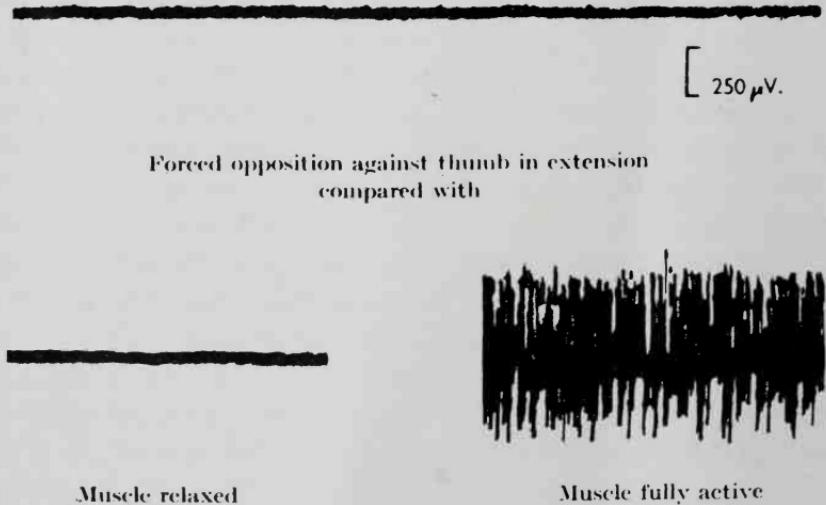
Fig. 90. EMG's of second lumbrical muscle while middle finger is in different positions. (From Backhouse and Catton, 1954.)
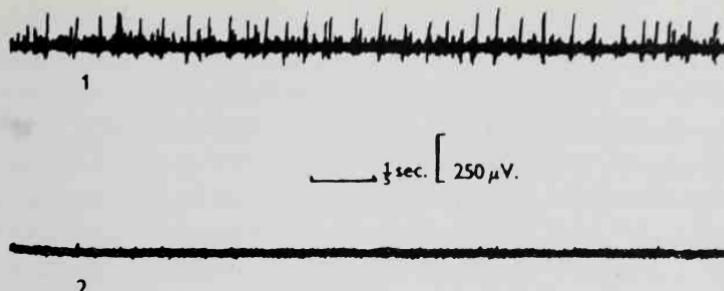
FIG. 91. EMG's of lumbrical. *1*, relaxed in extension with ulnar deviation, and *2*, radial deviation against resistance. (From Backhouse and Catton, 1954.)

tension of the proximal joint, the distal joint had to be extended simultaneously, but the position of the MP joint was not important.

Meanwhile, Brown, Long and Weiss (1960) and Long *et al.* (1960, 1961) at Western Reserve University in Cleveland have completed a comprehensive and ingenious study of the hand musculature, the results of which add to our understanding of its kinesiology. Using multiple, indwelling, pliable wire electrodes, this group has shown that the interossei of the hand act as MP flexors only when their other action of IP extension does not conflict. Therefore they act best and strongest when combined MP-flexion—IP-extension is performed. During all IP extension, the intrinsic muscles of the hand contract regardless of MP posture.

They concluded that the long tendons of the fingers provide the gross motion of opening and closing of the fist at all the joints simultaneously. However, the intrinsic muscles perform their major function during any departure from this simple total opening or closing movement. Thus, they are the primary IP extensors while the MP joints are flexing.

Long and Brown (1962, 1964) confirmed and expanded on their preliminary findings for the lumbricals. In general, these findings confirm those of Backhouse and Catton (see above). The lumbricals are silent during total flexion of the entire finger, but are very active whenever the proximal or distal IP joints are extended

actively or are held extended while the MP joint is flexed actively. The lumbricals can be kept very quiet during MP movements in any direction by keeping the IP joints fully flexed.

To summarize, Long and Brown conclude that the interossei and the lumbrical of one finger do not form a functional unit— they act discretely. The interossei participate in IP extension only when the MP joint is either flexing or held flexed. The lumbrical always takes part in interphalangeal extension. It shows a crescendo of activity throughout the movement, reaching a peak at full extension. This suggests that its function may include prevention of hyperextension at the MP joint. Neither the interossei nor lumbrical of the middle finger acts during closing of the full hand, suggesting that in this total movement they are not synergists.

The activity of the long extensors and flexors occurs in special sequences. Extensor digitorum acts during MP extension—in both the movement and the "hold" position. But it is also active in many flexion movements of that joint, apparently acting as a brake. The flexor profundus is the most consistently active flexor of the finger. Joined by the flexor superficialis, the profundus may act as a flexor of the wrist joint also. The superficialis has its maximal action when the hand is being closed or held closed without flexion of the distal IP joint.

Thenar and Hypothenar Muscles

The electromyography of the thenar and hypothenar muscles has been neglected until very recently, possibly because of the close packing of these small muscles. The French pioneers, Tournay and Fessard (1948), and Weathersby (1957) made useful, but brief, preliminary reports; this was followed by a longer report by Weathersby et al. Otherwise, no substantial work appeared until 1965 when Forrest and I published a systematic study with fine-wire electrodes; this paper will be heavily drawn upon in the subsequent paragraphs.

The report of Tournay and Fessard was concerned with general phenomena rather than with particular actions of the thumb

muscles. Weathersby found with surface and needle electrodes that each of the thenar muscles was involved to some extent in most of the movements of the thumb. The abductor pollicis brevis contracts strongly during opposition and flexion of the thumb as well as in abduction. The opponens shows strong activity in abduction and flexion of the metacarpal as it does in opposition. The flexor pollicis brevis shows considerable activity in opposition as well as flexion, and in adduction. The adductor pollicis (which is, of course, not properly a thenar muscle) is active in adduction and opposition, and, to a slight extent in flexion of the thumb.

It is interesting to note that Sala (1959) of Pavia, Italy, used electromyography combined with nerve stimulation to determine the innervation of the muscles of the thenar eminence. He found that one out of every four flexor brevis muscles was exclusively supplied by the ulnar nerve, while in almost all the remainder both ulnar and median nerves shared in the supply. These findings are quite contrary to classical teaching. Opponens pollicis was supplied exclusively by the median nerve in two-thirds of cases only, most of the remaining one-third having a double supply. He reported frequent bilateral asymmetry; this is disturbing, to say the least, when one considers the practical difficulties introduced into clinical examinations.

Our series in the emg study of the thenar and hypothenar muscles included 25 young adult subjects. A preliminary detailed study in the dissecting room gave a thorough knowledge of the anatomy, relationship and landmarks of the muscles concerned and provided an opportunity to practise and perfect the placement of electrodes. Their location in the middle of a muscle belly gives the truest picture of the general activity of that muscle. In the case of the flexor pollicis brevis, the electrode was inserted into superficial fibres corresponding to the portion of the muscle described by Jones (1942) as the superficial or external head; this arises from the flexor retinaculum and trapezium, passes along the radial side of the tendon of the flexor pollicis longus, and inserts into the radial sesamoid bone of the metacarpophalangeal joint and the base of the first phalanx of the thumb.

All movements began with the subject's hand in the rest position, in which, of course, there were no action potentials. The subject then moved his hand into a series of prescribed positions. Movement was performed slowly, each position was held for several seconds, and then the hand was returned slowly to the rest position. Positions of opposition were held either softly (with thumb and finger just touching), or firmly (with just enough pressure to resist the withdrawal of a sheet of paper from between the thumb and finger). Objects (a cup, glass or dowel) were held firmly, that is, securely, but with much less than maximum strength and effort. Although recordings were made during the entire movement, only those from the active positions are considered here, *viz:*

1. *Of the thumb:*

   A. Extension (movement away from the radial side of the palm and index finger in the plane of the palm);

   B. Abduction (movement away from the radial side of the palm and index finger in a plane 90° to that of the palm);

   C. Flexion (flexion of the interphalangeal, metacarpophalangeal and carpometacarpal joints of the thumb in a plane parallel to that of the palm so as to scrape the ulnar side of the thumb lightly across the palm);

2. *Of the little finger:*

   A. Extension (full extension of all the joints of the little finger);

   B. Abduction (movement away from the ring finger in the plane of the palm);

   C. Flexion (90° flexion of the little finger at the metacarpophalangeal joint with both interphalangeal joints almost fully extended).

3. *Eight positions of opposition* in which the thumb was held *softly* opposed to each finger in two ways—with the pad of the thumb to the lateral side of the bent finger near its tip, and with the thumb and finger tip-to-tip, roughly forming the shape of the letter O (this series began with position one, opposition to the side of the index finger—as in figure 92, a—and position two, opposition to the tip of the same finger, and then proceeded in a
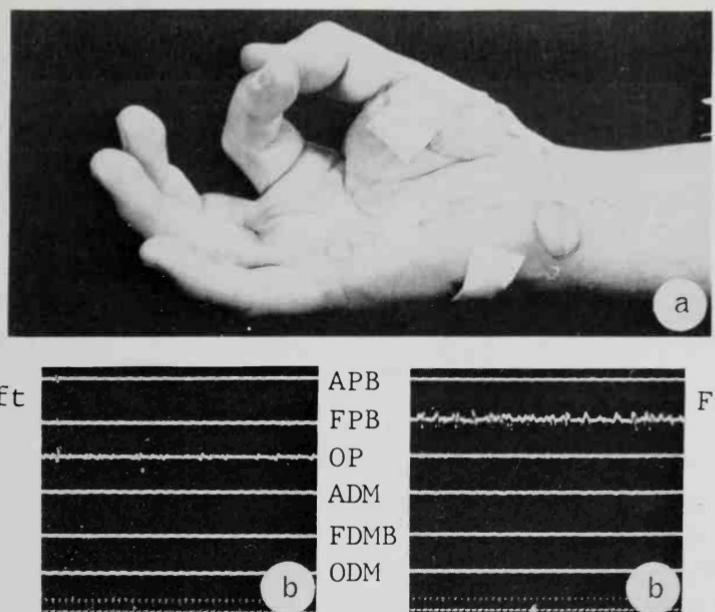
FIG. 92. *a*, opposition of the thumb to the side of the index finger (position one); *b*, electromyographic recordings during soft and firm opposition, respectively. (From Forrest and Basmajian, 1965.)

similar fashion to the long, ring and little fingers, ending with position eight, tip-to-tip opposition to the little finger—as in figure 93, a);

4. *The same eight positions* with *firm* opposition;

5. *Clasping* firmly a wooden dowel one inch in diameter;

6. *Holding*, in turn, two inches above the table, first a glass of water and then a cup of water by the handle while the subject sat with elbow unsupported and flexed to 90°.

Postures of Thumb

During extension, only the opponens pollicis and abductor pollicis brevis showed appreciable activity, which was moderate on the average. During abduction, the same two muscles showed marked activity on the average whereas the activity of the flexor pollicis brevis was slight. During flexion, the mean activity of
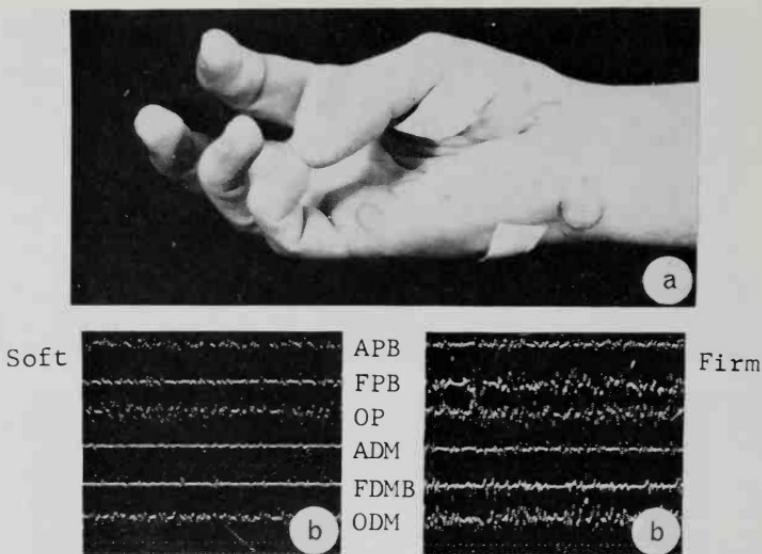
FIG. 93. *a*, opposition of the thumb to the little finger, tip-to-tip (position eight); *b*, electromyographic recordings during soft and firm opposition, respectively. (From Forrest and Basmajian, 1965.)

the flexor pollicis brevis was moderate to marked, but the opponens pollicis was only slightly active and the abductor pollicis brevis was essentially inactive.

The occurrence of equal levels of activity in both the abductor pollicis brevis and the opponens pollicis during extension and abduction of the thumb cannot be rationalized on the basis of their insertions. These are such that these muscles would be expected to move the thumb in opposite directions, especially during extension and to a lesser extent during abduction. Weathersby, Sutton, and Krusen (1963) suggested that stabilization of the part in order to produce a smooth, even motion was a possible explanation for the significant activities of muscles in situations such as this. This would seem to be a valid explanation.

Not all thenar muscles were active during extension and flexion of the thumb. Only three subjects showed more than slight activity in the flexor pollicis brevis during extension, the mean activity being *nil*-to-negligible. During flexion, the abductor

pollicis brevis exhibited negligible activity; the opponens pollicis, slight activity on the average; and the flexor pollicis brevis, moderate-to-marked activity. Indeed, in the position of flexion, 10 of the 25 subjects had *nil* or negligible activity in both the opponens and abductor while the flexor was significantly active.

In one other position there was coincident activity and inactivity in the thenar muscles. During firm pinch between the thumb and side of the flexed index finger (position one), only negligible activity was recorded from the abductor pollicis brevis. Yet the opponens pollicis, and, in particular, the flexor pollicis brevis were significantly active.

Postures of Little Finger

During extension of the little finger, all three hypothenar muscles were rather inactive on the average; but in many subjects the activity in one or more of the three muscles was negligible or *nil*. During abduction, although the abductor digiti minimi fulfilled the function indicated by its name and was the dominant muscle (with a mean of moderate-to-marked activity), the two other hypothenar muscles were also significantly active. During flexion, moderate-to-marked activity occurred in all three hypothenar muscles.

The abductor digiti minimi was very active during flexion of the little finger at the metacarpophalangeal joint. (The participation of this muscle in this position of the finger is obvious also by palpation.) Part of the explanation for this activity depends on the muscle's insertion into the ulnar side of the base of the proximal phalanx. The abductor digiti minimi was also significantly active when the thumb was held opposed to either the ring or little finger. Some of this activity is possibly associated with the small degree of flexion at the fifth metacarpophalangeal joint that is required when the thumb and little finger are opposed. Yet, such flexion is obviously not required during opposition of the thumb and ring finger. Some of the activity of the abductor digiti minimi, then, may be to provide stability; and simple abduction of the little finger may be the least important function of the abductor of this finger.

Positions of Opposition

During soft opposition of the thumb to the side and tip of each finger (positions one through eight), gradual increases in activity were recorded from all six muscles, starting at position one in the case of the thenar muscles and beginning at position five in the case of the hypothenar muscles (figs. 93,b and 94). The opponens was the most active of the thenar muscles; the flexor was the least active (fig. 92,b). The opponens digiti minimi was the most active hypothenar muscle. All the thenar muscles were more active than the hypothenar muscles.
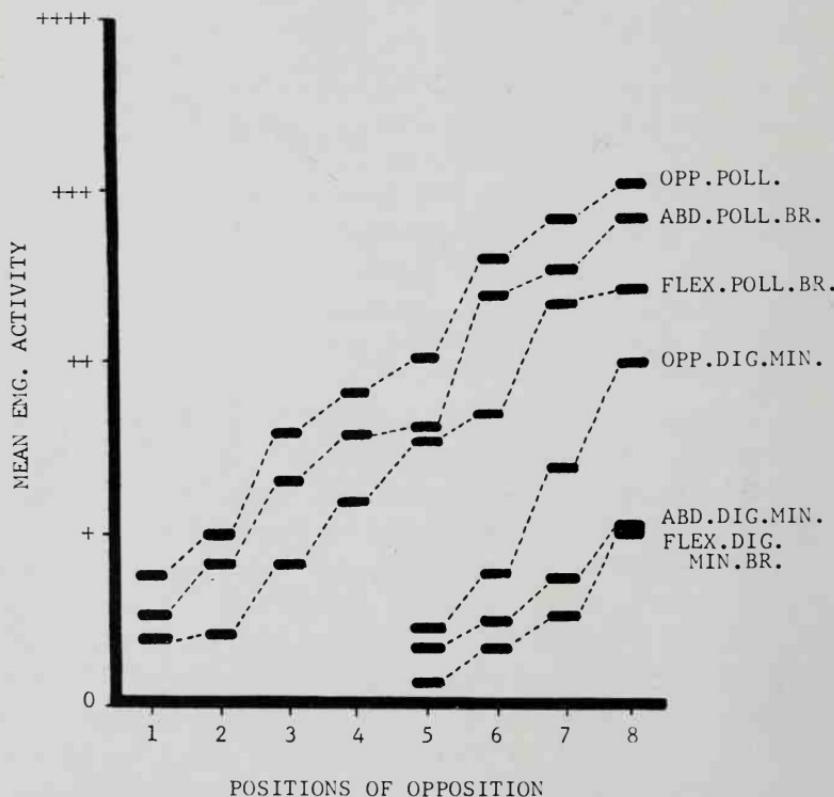
Fig. 94. Mean electromyographic activities during soft opposition of the thumb to side and tip of each finger, beginning with the side of the index finger (position one) and ending with the tip of the little finger (position eight). (From Forrest and Basmajian, 1965.)

FLEX.POLL.BR.
OPP.POLL.
OPP.DIG.MIN.
ABD.POLL.BR.
FLEX.DIG.
  MIN.BR.
ABD.DIG.MIN.

MEAN EMG. ACTIVITY

POSITIONS OF OPPOSITION
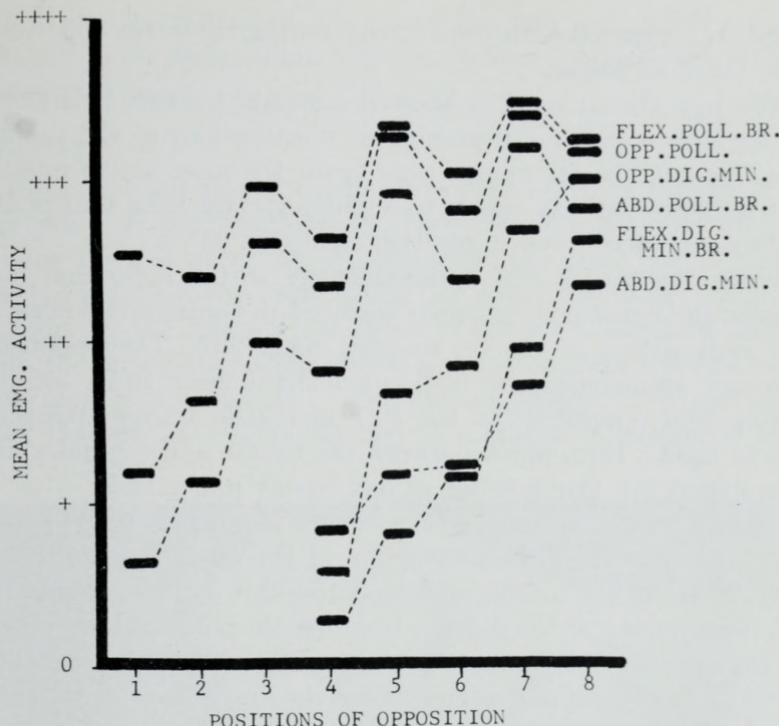
Fig. 95. Mean electromyographic activities during firm opposition of the thumb to the side and tip of each finger, beginning with the side of the index finger (position one) and ending with the tip of the little finger (position eight). (From Forrest and Basmajian, 1965.)

When opposition was firm (fig. 95) the flexor pollicis brevis replaced the opponens pollicis as the dominant muscle, particularly in positions one to four (index and long fingers) (fig. 92,b). In positions five to eight, the activity of the opponens pollicis approached and then equalled that of the flexor pollicis brevis. The abductor pollicis brevis was the least active of the thenar muscles (fig. 93,b).

The steady increase in thenar-muscle activity from position one through eight seen during soft opposition was not observed during firm opposition. Instead, higher levels of activity were usually recorded during firm opposition of the thumb to the side of the

finger as compared with the activity during tip-to-tip opposition with the same finger.

The hypothenar muscles showed a steady increase in activity during firm opposition beginning at position four of the thumb. The opponens digiti minimi was again the most active muscle, and its mean activity was even slightly greater than that of the abductor pollicis brevis in position eight (fig. 93).

When the thumb was opposed firmly to the index and long fingers, the flexor pollicis brevis replaced the opponens pollicis as the most active of the six muscles (fig. 92,b). The opponens, however, approached and then equalled the flexor in its activity during firm opposition to the ring and little fingers (positions five to eight). Firm pinch between the thumb and the index and long fingers is a grip position of day-to-day importance.

Little (1960) attributes to the flexor pollicis brevis and to the mechanically advantageous position of the adductor pollicis the great power of the thumb, which enables this digit to balance the combined power of the fingers. Ignoring the contribution of non-thenar muscles such as the adductor (which we are presently investigating) our findings emphasize the importance of the short flexor in thumb power. Weathersby, Sutton, and Krusen (1963) also noted an increase in flexor activity as the subject pressed lightly with the thumb and index finger in a position corresponding to our position two.

One may observe that the greater the medial rotation of the first metacarpal, the greater is the tendency of the head of the fifth metacarpal to be drawn in an anterolateral (volar-radial) direction. The opponens digiti minimi is mainly responsible for this movement of the fifth metacarpal, and its action is almost reflexive in nature. The more active the opponens pollicis is in medially rotating the first metacarpal, the more active the opponens digiti minimi becomes. But the opponens pollicis is always the more active muscle. It is possible that beyond a certain degree of medial rotation of the first metacarpal, the two opponens muscles begin to act in unison to form the transverse metacarpal arch mentioned by Littler (1960) and by others. Indeed, this

might be expected when one views the two opponens muscles, with the flexor retinaculum between, linking up the first and fifth metacarpal bones.

Positions of Grip

The important role of the flexor pollicis brevis in firm grasp is illustrated in the positions of firmly clasping a dowel and of holding a cup of water (fig. 96). Although the flexor pollicis brevis was the most active muscle while the dowel was grasped firmly, this was not the case when the glass of water was also held firmly. Both the opponens pollicis and the abductor pollicis brevis were then more active (fig. 96). This finding, and other preliminary work that we have done, has led to a tentative conclusion that
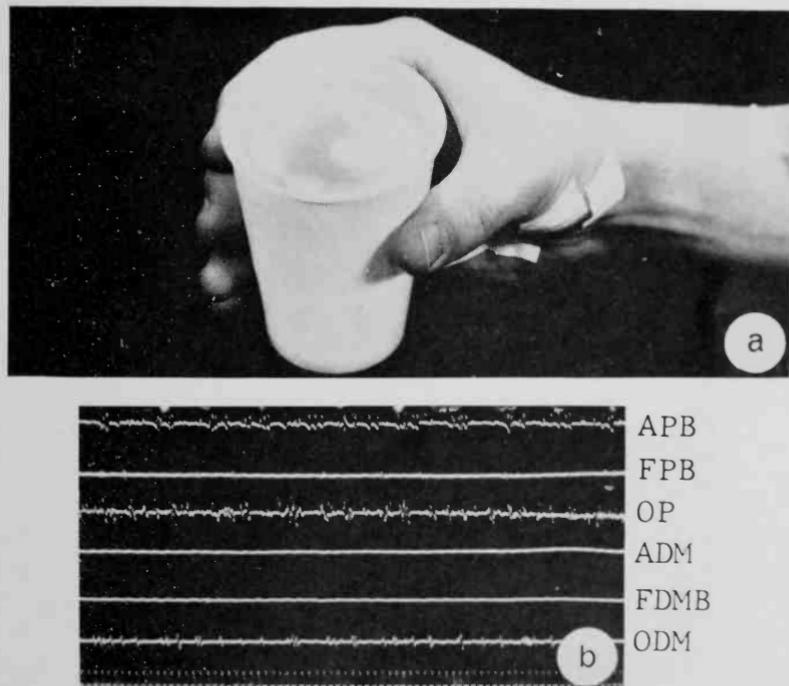
Fig. 96. *a*, holding a glass of water; *b*, electromyographic recording. (From Forrest and Basmajian, 1965.)

the more the thumb is abducted (as in holding the glass), the less the flexor brevis contributes to a firm grip. The activity of this muscle, which provides firmness of grip when only a small degree of abduction exists (as in holding the cup), is replaced by that of the opponens when a large amount of abduction is present (figs. 97, 98). In the absence of significant flexor activity, this activity of the opponens, coupled with that of the abductor, provides the power of a firm grip.

In summary, not all thenar muscles are active in all thumb positions; but all hypothenar muscles are active in three basic postures of the little finger. Two somewhat different patterns of activity occur when the thumb is first softly and then firmly opposed to each of the fingers in a sequence that begins at the index
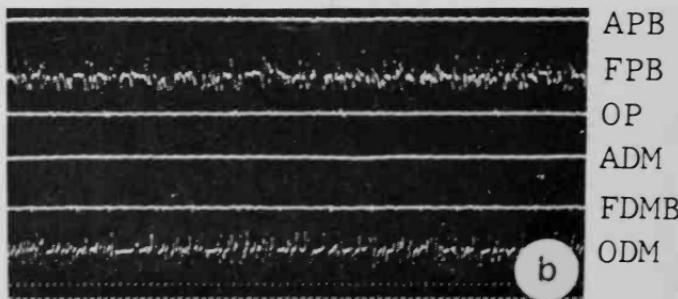
FIG. 97. *a*, holding a cup of water; *b*, electromyographic recording. (From Forrest and Basmajian, 1965.)
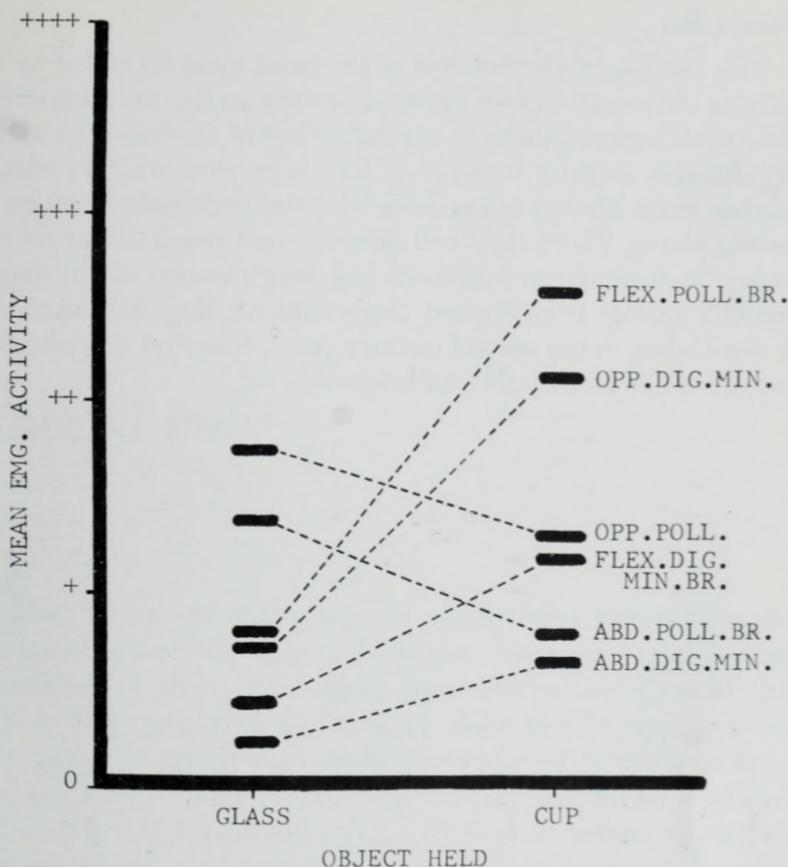
Fig. 98. Holding a glass and cup of water: mean emg activities compared. (From Forrest and Basmajian, 1965.)

and ends at the little finger. The flexor pollicis brevis is dominant in firm grip, particularly in grip between the thumb and two radial fingers; but a large degree of abduction of the thumb might possibly be a limiting factor in the activity of this muscle. The two opponens muscles seem to act as a unit in opposition of the thumb to both the ring and little fingers. Certain activity in some of the six muscles and inexplicable on a morphological basis probably serves to provide stability.

Conclusion

This section on the muscles of the hand must be ended by ad-
mitting the need for much systematic work on this most important
functional region. Finally, a careful review of Duchenne's classical
experiments is time well spent for those who wish to enlarge
further upon the now available electromyographic findings re-
ported above. There they will discover that much of our current
understanding of the interossei and long muscles of the fingers
actually springs from ancient times. Indeed, they will learn that
it was Galen, in the second century A.D., who first described the
actions of the lumbricals and interossei.

Lower Limb

B<small>ECAUSE</small> of its importance in posture and locomotion and because of its accessibility and large size, the lower limb has been the subject of electromyography from the earliest days of this science. The quality of the research done in this region of the body has been spotty and many unwarranted conclusions have been made and—quite fortunately—largely ignored by textbook writers. Part of the trouble stems from poor technique that in turn arises from inexperience. Novices seem to be especially prone to doing their earliest studies on the lower limb. Furthermore, some of them seem to have become completely overcome by their initial effort and stopped publishing completely. One can only hope that this was occasioned by remorse.

The muscles of the limb will be discussed from above downwards. Reference has already been made to the postural functions of these muscles in Chapter 8. Therefore, some repetition is unavoidable and, indeed, desirable. Locomotion is treated as a special chapter (p. 253) but will be referred to wherever necessary in this chapter also.

Hip Region

The muscles of this region which have been studied by various investigators and which will now be considered are: iliopsoas, the gluteal muscles and tensor fasciae latae. Other muscles that cross the hip joint (adductors, hamstrings, rectus femoris, and sartorius and gracilis will be considered with the muscles of the thigh, p. 215).

Iliopsoas

Recent advances in the surgery of the hip joint have focussed attention on the muscles of the region. Interest in the functions of iliopsoas in particular has been renewed by the novel surgical procedure introduced by Mustard of Toronto (1952) in which the insertion of iliopsoas is transplanted to the greater trochanter to substitute for paralyzed abductor muscles. Mustard finds that the resulting restoration of stability to the pelvis greatly outweighs the reduction of flexor power. The remaining flexor muscles are quite capable of providing any needed flexion for ordinary functions (Mustard, 1958).

When one begins to search the usual source-books for precise information about the actions and functions of iliopsoas, the only point that is agreed upon by all is that the muscle is obviously a flexor of the hip and probably has some influence on the lumbar vertebrae. There is a confusing disagreement about the other influences produced by the muscle. Last (1954) ascribes medial rotation of the hip mainly to the "powerful pull of ilio-psoas." The American *Gray's Anatomy* edited by Goss (1959) states that it rotates the hip medially while the British *Gray's* edited by Johnston and Whillis (1954) is more cautious with "it produces a slight degree of medial rotation . . . " Lockhart (1951) in *Cunningham's Textbook* agrees with this. Woodburne (1957) agrees with Steendijk (1948) that iliopsoas rotates medially when the limb is extended and laterally when it is flexed. To complete the spectrum of opinion, at least a dozen major reference works (see Steendijk, 1948) state that iliopsoas is a lateral rotator.

In this running controversy that is now more than a century

old, almost everyone has lost sight of the principle that a muscle so close to a joint must have an important postural or stabilizing function.

There has been some disagreement in the electromyography of this muscle partly resulting from different techniques. Using surface electrodes over this deep and almost inaccessible muscle, Joseph and Williams (1957) concluded that iliopsoas is inactive in standing subjects. This was confirmed with fine-wire electrodes for iliacus by LaBan, Raptou and Johnson (1966) although my own investigation of iliacus with long needle electrodes (1958b) indicated a continuous slight to moderate activity during relaxed standing in four persons (fig. 99,A). Using bipolar fine-wire electrodes, Greenlaw and I (1966, unpublished) have found the psoas major also shows some slight to moderate activity during relaxed standing in eight normal young adults. The bipolar, Karma-wire electrodes (p. 32) were introduced from behind directly into the psoas in the midlumbar region. Similar findings have been made by R. B. Keagy of Chicago in post-operative subjects (1966, personal communication) and in several normal subjects by Close (1964). Although there seems to be a wide division of opinion here, the truth may be that there is very little real difference. What disagreement there is probably arises from differences both in technique and in the stance of subjects. In any case, the activity is not very marked.

ILIACUS. As one would expect, action potentials are recorded during flexion of the hip in almost any posture of the whole subject and in almost the whole range. The amount of activity varies directly with the effort or resistance. We find marked activity in iliacus throughout flexion of the hip during "sit-up in the supine position" (Greenlaw and Basmajian, unpublished). However, LaBan et al. found there was little or no activity in iliacus during the first 30° of hip flexion. But, during "sit-up" from the "hook-lying" position, considerable activity occurred during the entire movement. Flint (1965) reported considerable variation in the styles of doing sit-ups but generally got little activity through surface electrodes in the first 45° of flexion.
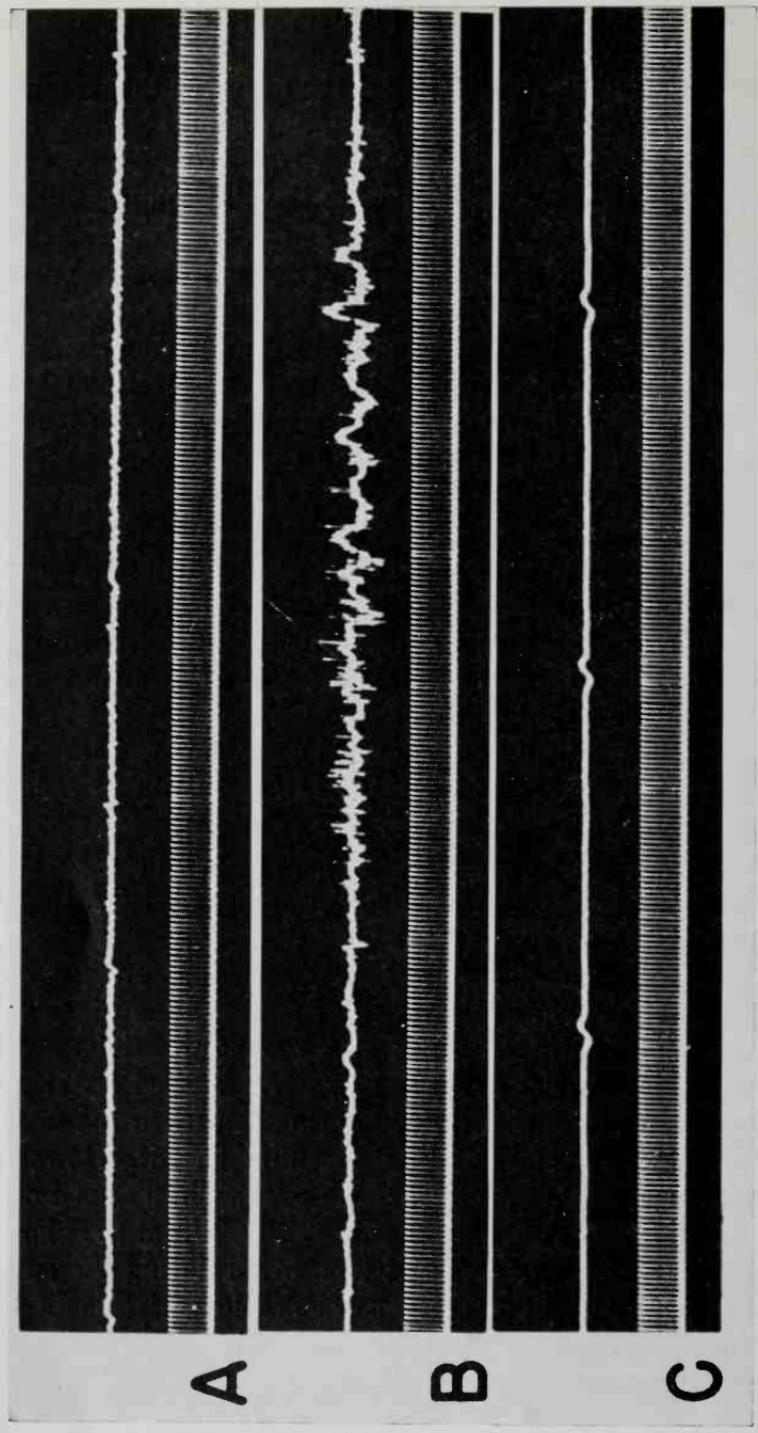
FIG. 99. EMG's of iliopsoas (time marker intervals equal 0.01 second). A, subject 1 standing relaxed, continuous slight activity; B, subject 2 standing relaxed, a burst of moderate, superimposed on slight, activity; C, lying relaxed, no activity except for electrocardiographic artifact. (From Basmajian, 1958b.)

In one of the four iliacus muscles in my earlier study, the records show intermittent short bursts of marked activity at irregular, short intervals during quiet standing; these apparently occur with invisible changes of position of either the limb or the trunk (fig. 99,B).

When our subjects lie down or sit at ease, and during extension, abduction and adduction of the joint, there is no activity (fig. 99,C). Both medial and lateral rotation of the hip joint produce some slight activity, whether the joint is passively or actively held in any of the extended, semiflexed or flexed positions (fig. 100). In two there is slight but equal activity in both directions; in the third there is somewhat more activity on medial rotation; and in the fourth, somewhat more on lateral rotation. LaBan *et al.* confirm these findings.

PSOAS MAJOR. Our direct recordings from psoas are strikingly similar to those from iliacus. Thus we get a slight activity during relaxed standing, strong activity during flexion in all of many trial postures, moderate activity in abduction, slight activity during both medial and lateral rotation and little activity during most other conditions involving the thigh. The only lumbar movement which consistently recruits psoas is a deliberate increase in lumbar lordosis while standing erect. (The details of this study will be enlarged upon in a future paper by Greenlaw and myself.) Robert Close (1964) emphasizes the abductor function of iliopsoas, which he found to be quite active during extreme abduction.

Nachemson's (1966) study of the vertebral part of psoas with coaxial needle electrodes dealt with vertebral effects. He concluded that psoas has a significant rôle in maintaining upright postures.

Iliopsoas—both its parts—appears to be an active postural or stabilizing muscle of the hip joint as well as a flexor (fig. 101). The controversy as to whether it is a medial or a lateral rotator should be abandoned because, in fact, it is neither one nor the other. Indeed, reviewing the work of Duchenne, one would find that he agreed with this conclusion although his view has often been misrepresented.
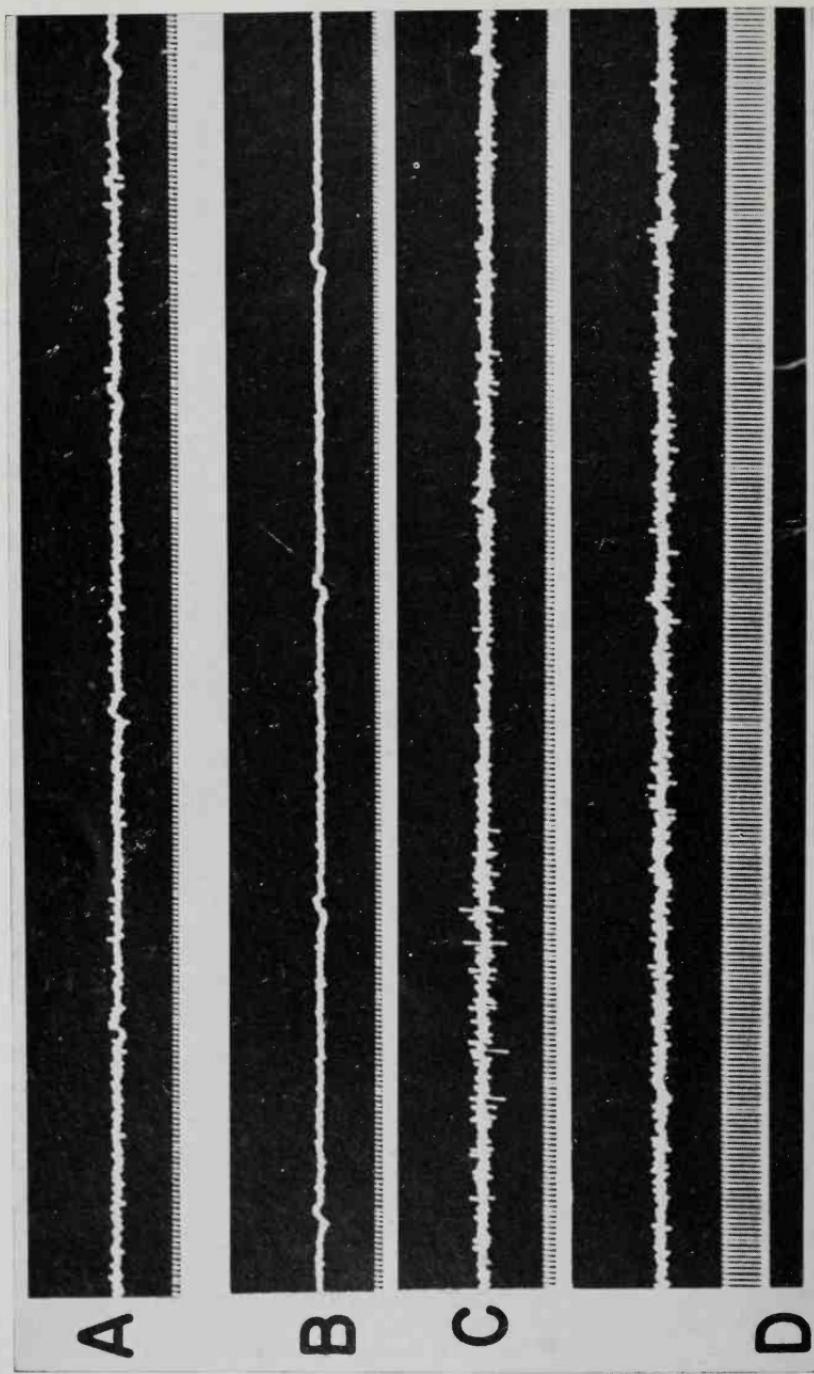
Fig. 100. EMG's of iliopsoas. *A* and *B* show activity during medial and lateral rotations of the thigh respectively in one subject. *C* and *D*, medial and lateral rotation in another subject. (From Basmajian, 1958b.)
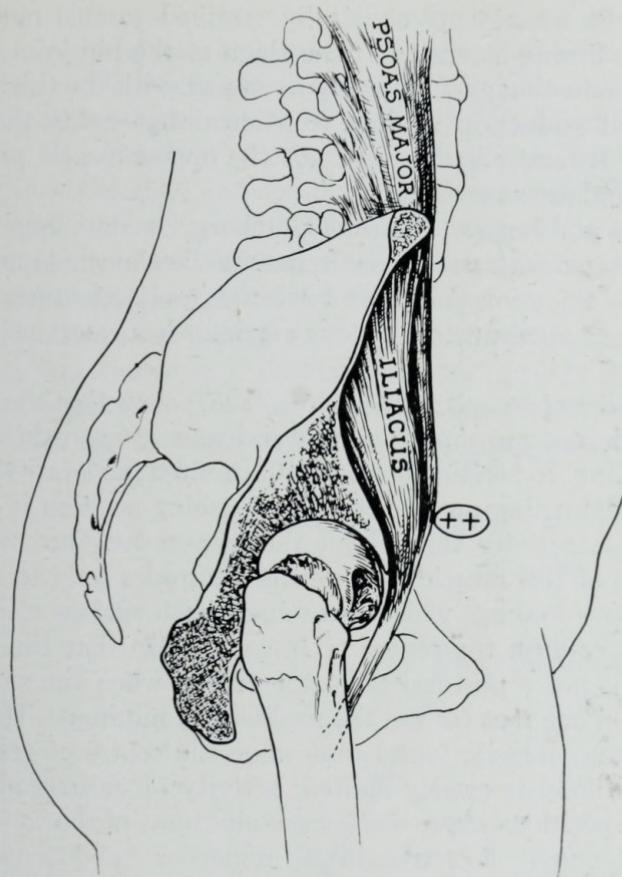
FIG. 101. Diagram of postural function of iliopsoas. It is moderately active continuously during standing.

The Glutei and Tensor Fasciae Latae

The gluteus maximus has usually been considered separately even where many muscles have been studied simultaneously, while the gluteus medius and gluteus minimus have usually been considered together because of their close association. Tensor fasciae latae is, of course, closely associated with the glutei.

GLUTEUS MAXIMUS. Wheatley and Jahnke (1951) in their research at the State University of Iowa concluded that the gluteus maximus was active only when heavy or moderate efforts were

made in the movements classically ascribed to this muscle. It was active during extension of the thigh at the hip joint, lateral rotation, abduction against heavy resistance with the thigh flexed to 90° and adduction against resistance that holds the thigh abducted. Lateral rotation (but not the opposite) also produced activity in gluteus maximus.

Karlsson and Jonsson (1965) of Göteborg, Sweden, found essentially the same with needle electrodes. While the whole muscle is engaged in extension and lateral rotation, only its upper part is abducent. As an abductor, gluteus maximus is a reserve source of power.

The studies of Joseph and Williams (1957) show that the gluteus maximus is not an important postural muscle even during forward swaying. In bending forwards it exhibited moderate activity. When straightening up from the toe-touching position it showed considerable activity throughout the movement. Our own sporadic tests of this muscle with needle electrodes tend to confirm all the above findings which were made with surface electrodes. They also confirm the report of Inman (1947) that the gluteus maximus is not a postural abductor muscle when the subject is standing on one foot (as are the medius and minimus). However, Karlsson and Jonsson found that when the centre of gravity of the whole body is grossly shifted, activity of gluteus maximus occurs. In positions where one leg sustains most of the weight, the ipsilateral muscle is active in its upper or "abducent" part; apparently this is to prevent a drooping of the opposite side. They also found that, during standing, rotation of the trunk activates the muscle that is contralateral to the direction of rotation (i.e., corresponding to lateral rotation of the thigh). Forward bending at the hip joint and trunk recruits gluteus maximus apparently to fix the pelvis. One of the chief values of the work of Karlsson and Jonsson is their showing the *range* of responses from their subjects—who showed considerable normal variation.

Duchenne's observation that complete paralysis of gluteus maximus in no way disturbs ordinary walking has often been noted but bears repeating here. Finally, Houtz and Fischer (1959) have found it to be unimportant in bicycle pedalling.

GLUTEUS MEDIUS AND MINIMUS. Though Inman's demonstration (1947) of marked emg activity in the abductors when the subject stands on one foot is hardly surprising, the reader is referred to his valuable 1949 paper in which he described various other factors as well (fig. 102). Similarly, the finding of Joseph and Williams (1957) that gluteus medius and minimus are quiescent during relaxed standing is to be expected. Our scattered studies with needle electrodes have also confirmed the usual teaching about these abductors—emphasizing their importance in preventing the Trendelenburg sign, during abduction of the thigh, and in medial rotation (anterior fibres). This last action is the only controversial one and seems now to be confirmed by our (unpublished) work. Houtz and Fischer (1959), from their electromyographic studies,

FORCE CURVE

Subject S.T. 9/3/45
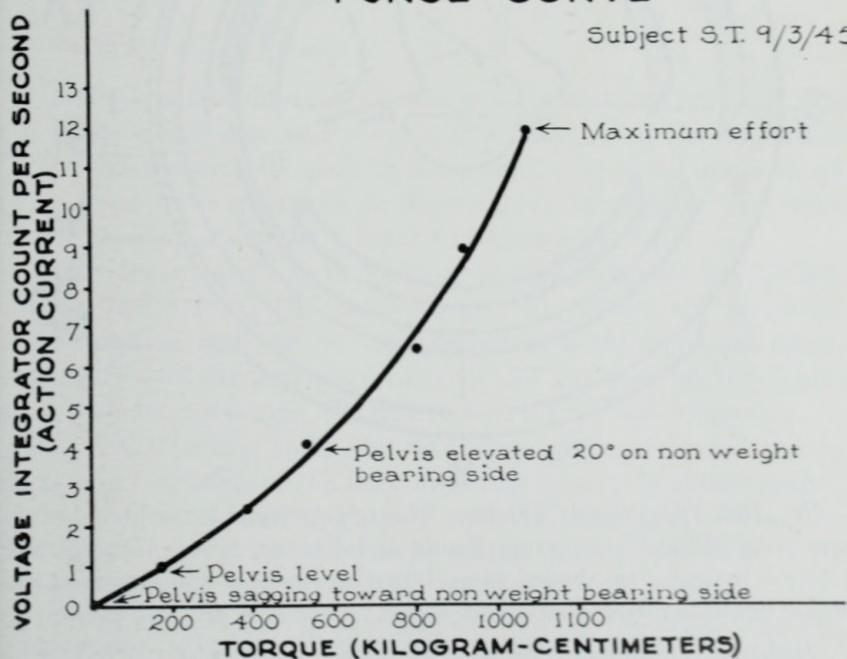
FIG. 102. A typical force curve, relating torque to action potentials of abductor muscles of the hip. (From Inman, 1947.)

concluded that the activity in all the glutei was minimal in bicycle pedalling (fig. 103).

TENSOR FASCIAE LATAE. Wheatley and Jahnke (1951) found action potentials in this muscle during flexion, medial rotation and abduction of the hip joint (and through the ilio-tibial tract it extends and laterally rotates the tibia at the knee joint). It was a
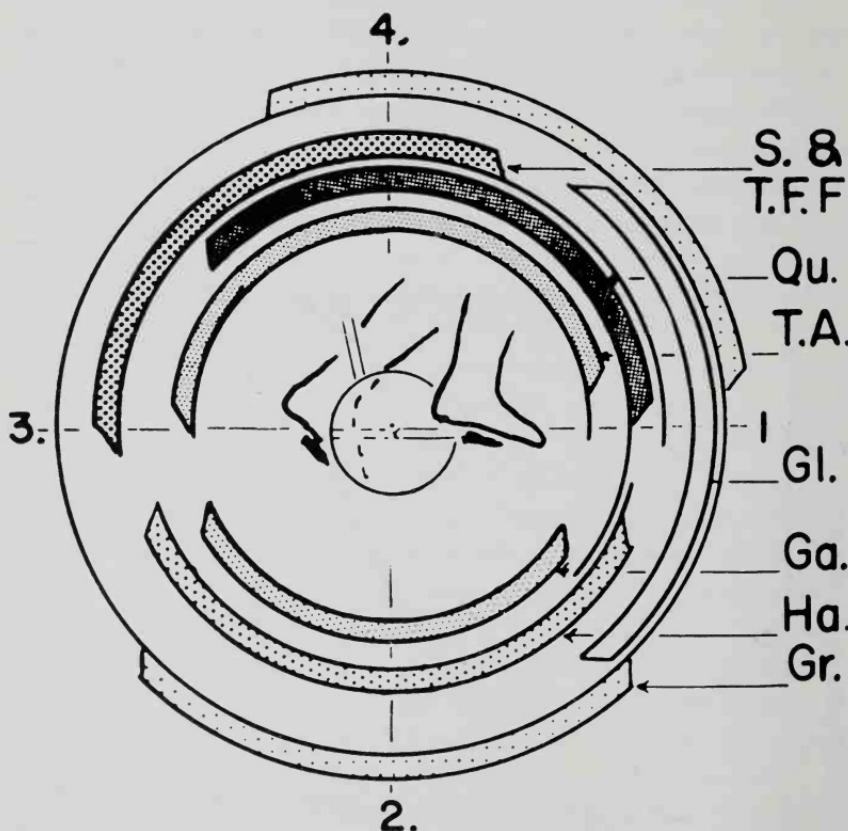
FIG. 103. Diagramatic summary of emg activity in lower limb during one cycle of bicycling. (From Houtz and Fischer, 1959.) Greatest activity is indicated by shaded areas, but where cycle is completed with a single line this means that slight activity continues. *Gr.*, gracilis; *S. & T. F. F.*, sartorius and tensor fasciae latae (femoris); *Qu.*, quadriceps; *T. A.*, tibialis anterior; *Gl.*, gluteus maximus and medius; *Ga.*, gastrocnemius; *Ha.*, hamstrings.

medial hip rotator in all positions. Duchenne clearly stated that the power of tensor fasciae latae as a rotator (in response to faradic stimulation) is weak, and with this I agree. Unlike the glutei, tensor fasciae latae is active during bicycling, showing its greatest activity as the hip is being flexed (Houtz and Fischer, 1959).

Thigh Muscles

The groups and single muscles to be considered now are the adductors (longus, brevis, magnus, gracilis and pectineus), the hamstrings (semimembranosus, semitendinosus and biceps femoris), sartorius, rectus femoris, the vasti (medialis, lateralis and intermedius) and the popliteus. Some of these cross the hip joint only (adductors), others cross both hip and knee (hamstrings, rectus, gracilis and sartorius), and still others cross the knee only (vasti and popliteus).

Adductors of the Hip Joint

In the first edition of this book, it was necessary to admit that "a surprising hiatus appears in our knowledge of the adductors. Forming an enormous mass on the medial side of the upper thigh, they must have considerable importance. In spite of this, their exact function is usually a matter of guesswork."

Since these words were written, Janda and Véle (1963) and Janda and Stará (1965) have helped to correct the situation. They studied the rôle of the adductors in children and adults during flexion and extension of both the hip and the knee, with and without resistance. (Care was taken to avoid rotation.)

In almost every child the adductors were activated during flexion or extension of the knee and they were very active against resistance. Most adults showed activity during flexion of the knee, but only a minority were active during extension. With resistance almost all adult subjects showed great activity.

During movements of the hip the rôle of the adductors was localized to their upper parts. During flexion against resistance, all the children and half the adults showed activity. During resisted extension, all were active.

Janda and Stará suggest that this labile response of the adductors is related to a postural response. They believe that these muscles are facilitated through reflexes of the gait pattern rather than being called upon as prime movers. With this view one can readily agree. Spruit's (1965) theoretical analysis of the adductors adds conviction to the opinion.

Recently, Machado de Sousa and Vitti (1966) studied the adductores longus and magnus (upper and lower parts) during movements of the hip joint. During free adduction the longus is always active while magnus is almost always silent unless resistance is offered. Both muscles are active during medial rotation but not during lateral rotation of the hip, settling a classic argument that usually leaned in the other direction. The upper fibres of adductor magnus showed the greatest activity.

During flexion of the thigh, de Sousa and Vitti found the main activity occurring in the adductor longus while the magnus is often completely silent. While standing in a relaxed natural posture, both muscles are inactive. However, weak activity sometimes appears when standing on one foot.

Gracilis which belongs "officially" to the adductor group will be considered separately below.

Hamstrings

The three hamstrings, biceps femoris, semimembranosus and semitendinosus, act on both hip joint and knee joint. Various studies including my own have shown that the first of these is active in ordinary extension of the hip joint (in contrast to gluteus maximus which acts only against resistance), and in flexion and lateral rotation of the tibia at the knee. Wheatley and Jahnke (1951) have shown biceps is active also in lateral rotation of the extended hip and in adduction against resistance of the abducted hip.

The semimembranosus and semitendinosus are active in extension and also during medial rotation of the hip, adduction against resistance of the abducted hip, and flexion and medial rotation of the tibia at the knee joint.

Joseph and his colleagues at Guy's Hospital Medical School (1954 *et seq.*) demonstrated the much greater stabilizing function of the hamstrings as compared with gluteus maximus, but emphasized their quiescence in ordinary standing. Portnoy and Morin (1956) agreed with them, as do my findings. In flexion at the hip and in leaning forwards, the hamstrings are much more active as supporters against gravity. Arienti (1948a, 1948b) of Milan, Italy, showed by emg studies performed while the subjects were walking on a treadmill that the hamstrings come into action at different stages of walking. It is not possible to forecast the exact phase of activity in a muscle during walking by only examining it while the limb is put through artificial tests of prime movers. For example, if semitendinosus and semimembranosus are examined while the two are producing a deliberate test movement, such as flexion of the knee, they are found to act synchronously. On the other hand, the semitendinosus flexes the knee during the swing phase of walking while semimembranosus acts mostly while the foot is on the ground. Arienti also showed that, although both heads of biceps femoris act synchronously during a free-moving test of flexion, the short head acts during the swing phase of walking while the long head acts as a stabilizer when the foot is on the ground.

Hirschberg and Nathanson of New York University made similar studies, reported in 1952. The hip muscles, quadriceps and hamstrings showed specific individual patterns being (in general) active during the transition from the swing phase to the stance phase (fig. 104). Only gluteus medius continued to contract beyond the middle of the stance phase; the others stop contracting within the first third of the stance phase. At the transition from the stance to swing, the adductor muscles (and sometimes the hamstrings) contract, according to Hirschberg and Nathanson.

There is now no doubt that the hamstrings do not by regional contraction act only on one joint. My studies of these muscles described in Chapter 7 (p. 128) showed that the entire muscle contracts regardless of whether the upper or lower joint was moved. Which joint is to move as a consequence depends on the immobilization of the other joint by other agencies.

Gl. Max.
Gl. Med.
Add.L.
Semitend.
Vastus L.
Gastroc.
Ant.Tib.
Foot Contact

swing   swing   swing

stance stance stance
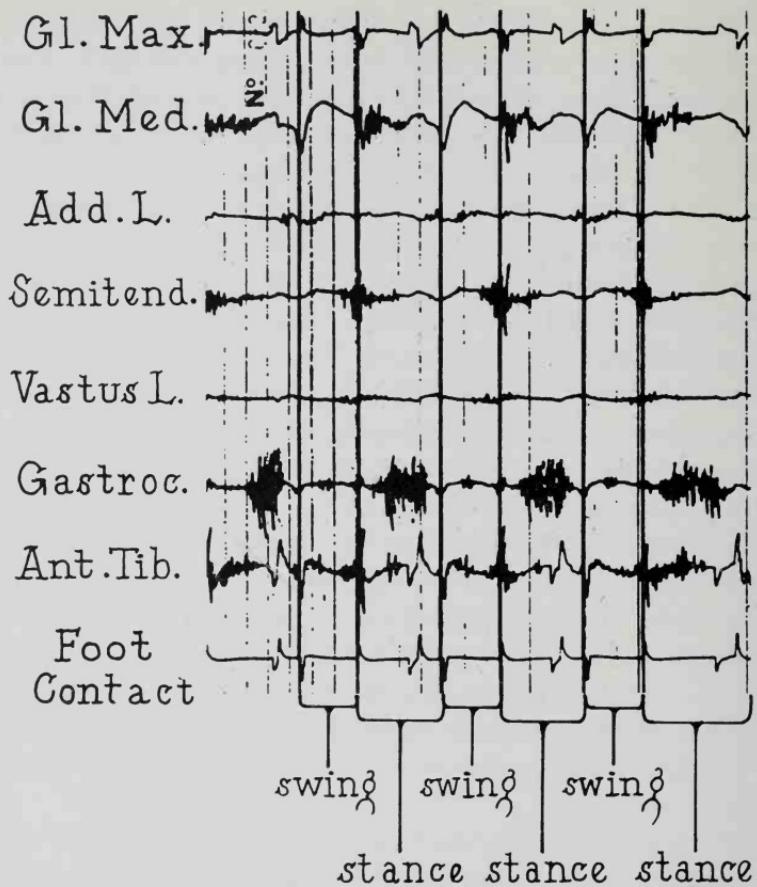
Fig. 104. EMG of normal gait. (From Hirschberg and Nathanson, 1952.)

Rectus Femoris

Undoubtedly, the rectus femoris is a flexor of the hip and extensor of the knee joint, and electromyography can only contribute information of secondary importance such as the timing of its activity in various movements. Because flexion of the hip is closely associated with extension of the knee, one is not surprised to find a single muscle performing these two movements. As with the hamstrings, my studies on two-joint muscles demonstrated

that normally the whole muscle contracts even with isolated movements of only one of the two joints.

Rectus femoris also aids in abduction of the thigh (Wheatley and Jahnke, 1951), and apparently is relaxed in ordinary standing. The studies of Joseph and Nightingale (1954), Joseph and Williams (1957), Portnoy and Morin (1956), Floyd and Silver (1950) and my own observations all agree on this. Houtz and Fischer (1959) showed a marked activity in rectus together with the vasti during the thrusting motion of bicycle-pedalling but not during the flexion of the hip joint.

Gracilis and Sartorius

Though belonging to the adductor mass, the gracilis crosses and therefore acts on both hip and knee. It is active in flexion of the hip with the knee extended but is inactive if the knee is allowed to flex simultaneously (Wheatley and Jahnke, 1951). It adducts the hip joint (and therefore it rightfully belongs to its parent group, the adductors) and it rotates the femur medially (Jonsson and Steen, 1966). Jonsson and Steen find that during flexion of the hip joint gracilis is most active during the first part of flexion both in free "basic movements" and during walking and cycling. In walking on a horizontal level and on a staircase, its activity occurs during the swing phase. At the knee it is a flexor and medial rotator of the tibia, although in medial rotation its activity appears to be slight, according to Jonsson and Steen. They also find it is insignificant in maintaining the standing posture. In bicycle pedalling it is not very active (Houtz and Fischer, 1959).

Sartorius is active during flexion of the thigh regardless of whether the knee is straight or bent, during lateral rotation of the femur or abduction of the thigh and during flexion of the knee joint or medial rotation of the tibia (Wheatley and Jahnke, 1951). Both sartorius and gracilis may play a rôle in the fine postural adjustments of the hip and knee although Joseph reports that he found no activity in sartorius during relaxed standing. In the bicycling experiments of Houtz and Fischer (1959), sartorius

showed its maximal activity during the thrusting phase of pedalling, as would be expected.

Vasti

The vasti, of course, are powerful extensors of the knee joint. Our experience agrees with that of many other investigators that the vasti are, however, generally quiescent during relaxed standing (Åkerblom, 1948, Kelton and Wright, 1949, Floyd and Silver, 1950, Portnoy and Morin, 1956, Joseph et al., 1954 et seq.). Joseph and Nightingale (1956) found that when women wear high heels activity appears in the vasti in a substantial proportion of subjects. Professor Arienti (see p. 217) has demonstrated that during walking on a treadmill, the three vasti and rectus femoris do not act synchronously but have a phasic pattern.

In 1957, a group, consisting of Mrs. W. E. K. Brown, Miss Rita Harland and myself, performed a series of electromyographic examinations of quadriceps femoris, the results of which are as yet unpublished. I am grateful to my physiotherapist colleagues for allowing me to report here some of the more significant results. Our subjects included 11 young women in whom simultaneous recordings were made from the vastus medialis, vastus lateralis and rectus femoris using skin electrodes and the special Stanley Cox multi-channel electromyograph described in Chapter 2 (p. 38).

Our chief concern was the evaluation of a number of standard procedures sporadically used in rehabilitation work ostensibly to help strengthen the quadriceps. For example, associated movements of the toes have been advocated to augment the activity of the quadriceps. More than half of our subjects showed no such augmentation. In those in whom augmentation of quadriceps did occur, the actually effective toe movement was flexion in some and extension in others.

Associated foot and ankle movements were somewhat more effective than toe movements in causing augmentation of quadriceps activity; this was true in most (but not all) of the subjects.

However, there was no clear-cut difference between the effects of any of the following: dorsiflexion, plantar flexion, inversion and eversion. All seemed to augment in some subjects, while one or other of the movements proved to be the most effective in others.

Medial or lateral rotation of the hip joint performed simultaneously with contraction of quadriceps had essentially no effect on the emg activity of quadriceps (except for some slight augmentation in one subject). Not only did simultaneous hip flexion fail to augment the amount of activity in quadriceps in most subjects, but it even decreased it in some.

The most effective technique for maximal motor unit activity was having the subject actively perform extension of the knee against resistance—not in a static position but during motion. Nonetheless, in many subjects, static contractions were just as effective—or even more effective—and therefore cannot be categorically condemned. The greatest activity during motion occurred in the last half (i.e., 90°) of extension. With static contractions, the position of the knee most effective for showing maximal activity in quadriceps was almost always the fully extended one.

In all our subjects, concentric actions caused more activity than eccentric ones, i.e., activity of the muscle during its primary action or shortening was considerably more than the activity while the muscle was acting as an antagonist or being forced to lengthen as it acted (negative work).

Flexion of the trunk or isolated contraction of the opposite quadriceps had little if any effect on the quadriceps under examination, suggesting that such techniques are practically useless for rehabilitation work. Simultaneous bilateral contraction of the quadriceps did not augment the activity in the one under study in some subjects while it did so in others. Finally, having the subject "push down" at the hip and knee regions (in an effort to hyperextend the knee joint actively) did not increase the activity of quadriceps, but actually diminished it in 3 of the 11 subjects. Instructing a patient to "push down your knee" is therefore not

an acceptable procedure for producing maximal quadriceps activity.

The lesson to be learned by physiotherapists and rehabilitation specialists from these findings is one of healthy scepticism for many of the dogmatic teachings that bear on the best methods of evoking maximal quadriceps activity. Some of our findings appear to confirm the dogmas, others flatly contradict them, and still others show that different subjects react in different ways.

Ravaglia's (1957) investigation of quadriceps femoris is also of interest. In a series of normal subjects he recorded *via* surface and needle electrodes from the vastus medialis, vastus lateralis and rectus femoris simultaneously. During the movement of rising from the sitting to the standing position and *vice versa*, the activity in the three heads was not synchronized and equal. The vastus medialis was retarded and was not as active as the other two. In erect standing the activity in the three heads fell rapidly. The vastus medialis was more active than the other two muscles examined. Ravaglia demonstrated conclusively that the three heads acted in different ways in various phases of movement.

Wheatley and Jahnke (1951) found a greater activity in vastus medialis when the knee was held in extension with the hip joint flexed or the knee joint (tibia) laterally rotated. On the other hand, the vastus lateralis was more active in extension of the knee when the hip was flexed or the knee joint (tibia) medially rotated. During resisted extension of the knee, the various parts of quadriceps came into action at different phases of the movement (fig. 105).

Popliteus

In an elegant piece of electromyographic research with needle electrodes on this small, deeply set muscle lying behind the knee, Barnett and Richardson (1953) confirmed the classical teaching (often denied) that it is a medial rotator of the tibia. Its activity at the start of flexion of the knee is related to the unlocking of the knee joint. When a person stands in the semicrouched knee-bent position, continuous motor unit activity of the muscle was demonstrated (see fig. 76 on p. 155). When the knee is bent the weight

TENSOR FASCIAE LATAE

SARTORIUS

RECTUS FEMORIS

VASTUS MEDIALIS

VASTUS LATERALIS

GRACILIS

↑180°

LEG EXTENSION (SITTING)
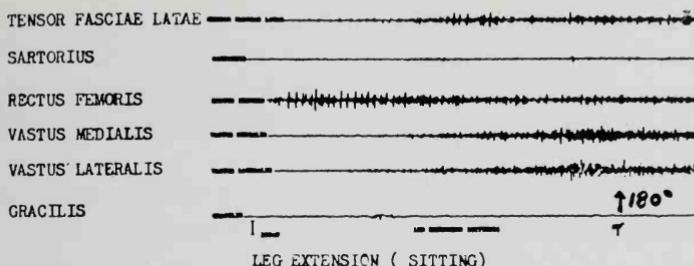
FIG. 105. EMG's of thigh muscles during extension of the knee from 90° to 180° (subject seated, limb hanging). (From Wheatley and Jahnke, 1951.)

of the body tends to slide the femur downward and forward on the slope of the tibia. It seems that the continuous marked activity of popliteus aids the posterior cruciate ligament in preventing forward dislocation.

Leg Muscles

We have elsewhere reported in detail an electromyographic study with needle electrodes of three muscles of the leg (and three intrinsic muscles of the foot) (Basmajian and Bentzon, 1954). The muscles of the leg were tibialis anterior, peroneus longus and the lateral head of gastrocnemius. An outline of the findings will now be given.

Most of the subjects were tested in different postures and during a variety of movements. Often, other muscles were examined as well. The first part of this section concerns only the findings in the muscles named during the "relaxed standing at ease" position. In this regard we were especially interested in testing the validity of the popular theory that peroneus longus, tibialis anterior and the intrinsic muscles of the foot maintain the arches of the foot in ordinary standing. Special attention was also paid to the possible influence of certain variable factors, such as the sex of the subject, the type of feet and the wearing of high heels by women.

For each muscle, records were made while the subject was reclining (as a control), immediately upon assuming the standing barefooted posture and after 2 minutes of standing. Considerable

testing showed that the initial activity invariably found on changing a position falls off rapidly to the resting level and that the 2-minute interval is adequate. Moreover, many of the subjects were tested at longer intervals (up to 15 minutes) with no change in the results.

Our "relaxed standing at ease" posture is the comfortable well balanced stance with the feet several inches apart and bearing equal weight, and with the hands clasped loosely behind the back. The relative position of the feet would show minor individual variations. However, the slight changes that were necessary for some subjects to conform to the standard position made no difference in their comfort or in the findings.

In the women, additional similar records were made from the muscles of the leg while high heels were being worn. The heels were all $2\frac{1}{2}$ inches high except in one case in which they were 3 inches.

The lateral head of gastrocnemius was active in the majority of subjects. In the women, the group showing continuous activity was definitely smaller when the subjects were barefooted, but, when high heels were worn, almost the same as in the males. A quarter of both men and women showed no electromyographic activity in this muscle when the subject stood barefooted. Analysis of individual cases revealed that only one of the women continued to show no activity with high heels.

Almost half of the men and a quarter of the women showed no electromyographic activity in tibialis anterior when standing barefooted (fig. 106). But another quarter of both the men and the women showed pronounced activity; this could be abolished by leaning forward. Each of the women in this latter group exhibited at least the same degree of activity on standing in high heels. One woman showed moderate activity while standing with high heels but only slight activity while standing barefooted.

Only 1 of 16 men and 2 of 16 women showed continuous activity in peroneus longus while standing barefooted. An additional man and 5 women showed intermittent activity. Half of the men and a third of the women showed inactivity when barefooted. With high heels, half of the women showed continuous marked activity and none showed inactivity in peroneus longus.
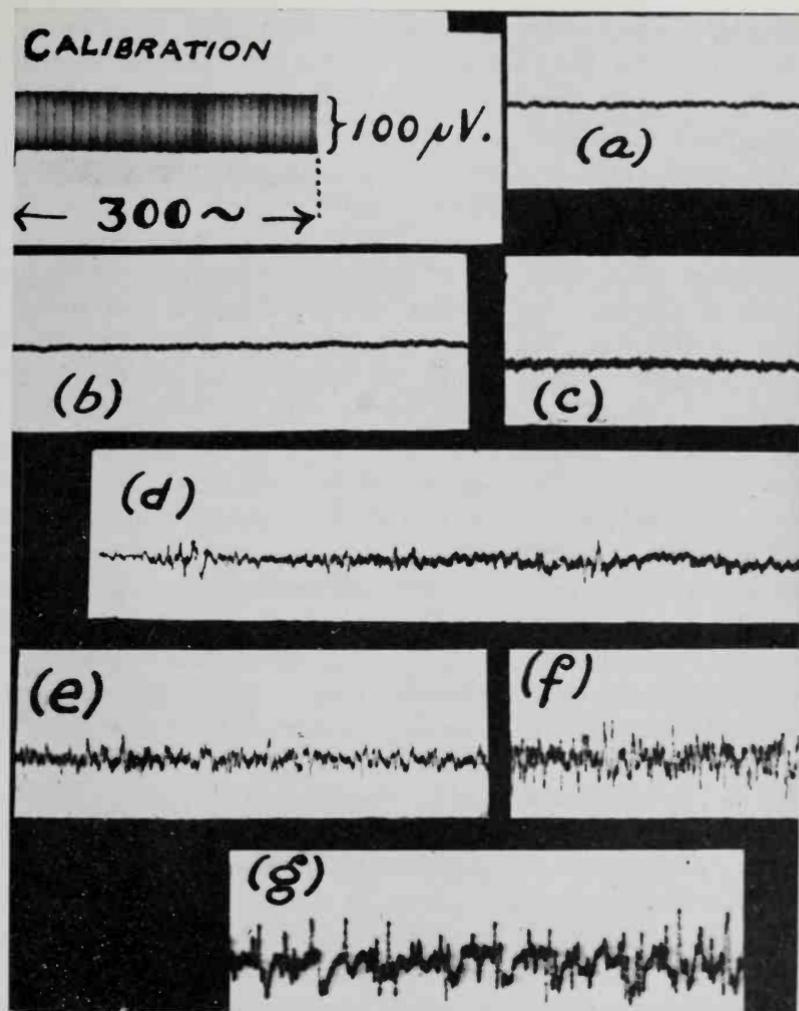
FIG. 106. Representative EMG's from leg muscles during standing: *a* and *b*, nil to negligible activity; *c*, slight; *d*, intermittent bursts; *e*, moderate continuous; *f*, and *g*, marked continuous.

There was no consistent significant relationship between the types of feet and types of activity in any muscle.

It now seems to be beyond controversy that the tibialis anterior and the peroneus longus (and, as we shall see, the intrinsic

muscle of the foot) play no important active rôle in the normal static support of the long arches of the foot. Our figures show that these muscles are completely inactive electromyographically in many normal individuals while standing. Smith (1954) came to the same conclusion after examining six subjects who all showed electromyographic quiescence in the anterior crural muscles during standing.

Although this investigation of predominantly normal feet showed no obvious relationship between types of feet and the types of activity in the muscles concerned during standing, no attempt is made to suggest that the muscles play no rôle in the abnormal flat foot. Furthermore, we are not dismissing the rôle of these muscles in the maintenance of the arch during locomotion. Indeed, the intrinsic muscles of the foot are always very active electromyographically when one rises on the toes to even the slightest degree (see below).

In so far as the muscles of the leg are concerned, the results showed a biological range of activity and were not in accord with some of the absolute findings of Smith, Joseph and Nightingale, and Åkerblom. We find that in the relaxed standing at ease position, there is activity in some individuals in the tibialis anterior and peroneus longus and that this can be abolished easily by unusual and varying stances or by the removal of weight from the limb. The disagreement probably stems largely from our use of the more sensitive needle electrodes rather than simple skin electrodes (fig. 107).

Joseph and Nightingale were concerned with soleus, gastrocnemius and tibialis anterior. In their subjects they found continued activity in every soleus and in some gastrocnemii, but none in tibialis anterior (fig. 108). Since their original paper they have added to their series with no change in their conclusions (Joseph, 1960). Granit's (1960) statement that, in general, mammalian soleus is tonic and gastrocnemius phasic may bear on this matter. However, Smith (1954) found that what postural activity there was in human legs during standing was intermittent and confined to gastrocnemius and not soleus. Levy (1963) finds that in man
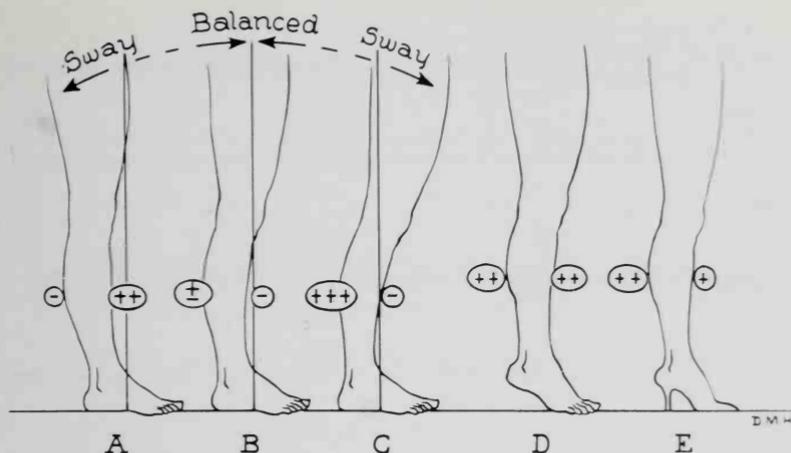
FIG. 107. Diagram of emg activity in anterior and posterior muscles of the leg under differing conditions.

soleus produces greater reflex contraction than gastrocnemius during the ankle jerk. He suggests that a greater density of muscle spindles in soleus (now generally accepted) accounts for this. One might expect a greater sensitivity to stretch in soleus.

The increased activity in all three of the muscles of the leg when high heels are worn may seem to be due to the element of instability introduced by the posture (fig. 107). But it will be noted that gastrocnemius and peroneus longus are involved and that tibialis anterior is not affected to any great extent. In another series of experiments we found that peroneus longus is markedly active in plantar flexion of the ankle. It appears, then, that the wearing of high heels shifts the centre of gravity forward to a new position in many women with a resultant increase in the activity of gastrocnemius and peroneus longus.

Joseph and Nightingale (1956) confirmed our finding that the wearing of high heels caused an increase in activity of the calf muscles (specifically soleus) in most women (fig. 109). They investigated the line of gravity in 11 women and found that it bore no constant relationship in spite of their reluctance to agree to the occurrence of intermittent activity of the leg muscles in stand-
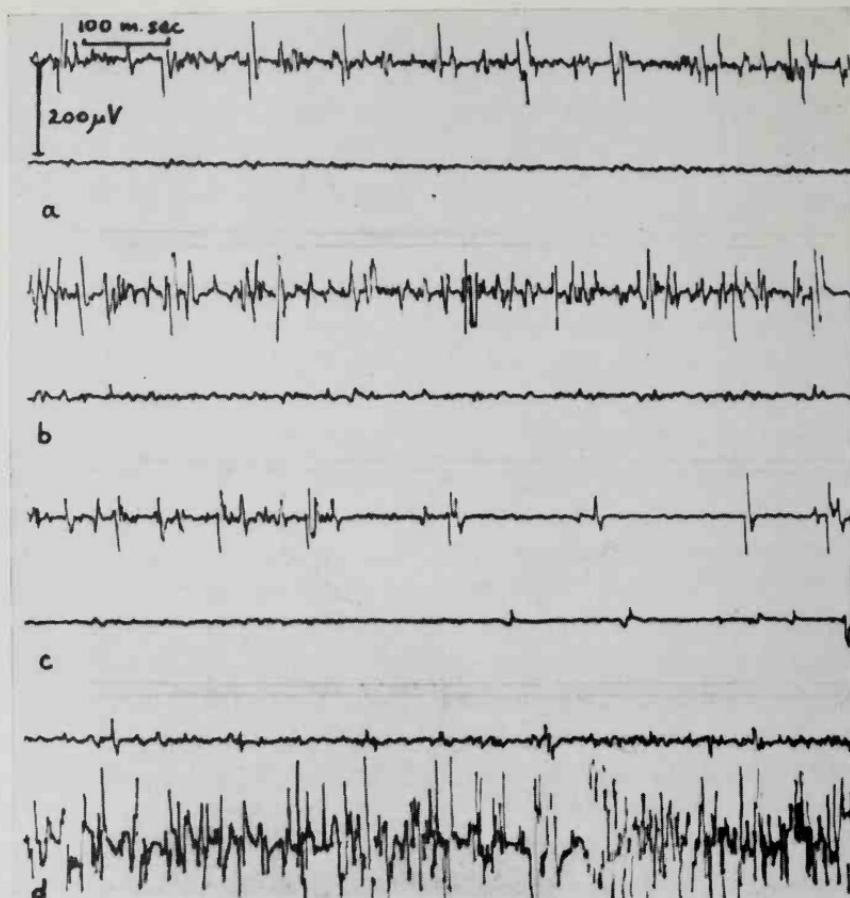
Fig. 108. EMG's from soleus (*upper trace*) and tibialis anterior (*lower*). *a*, Standing at ease; *b*, after swaying forwards; *c*, while swaying backwards; and *d*, after swaying backwards. (From Joseph, 1960.)

ing. They also established beyond a doubt that the swaying forwards and backwards of a subject by as little as 5° produces reflex activity of the posterior and anterior leg muscles.

Portnoy and Morin (1956) tended to confirm our findings, reporting that five gastrocnemii showed intermittent activity while 9 (of 16) showed continuous activity during relaxed standing. Naponiello (1957) reported similar intermittent activity in tibialis anterior with or without high heels, as did Floyd and Silver
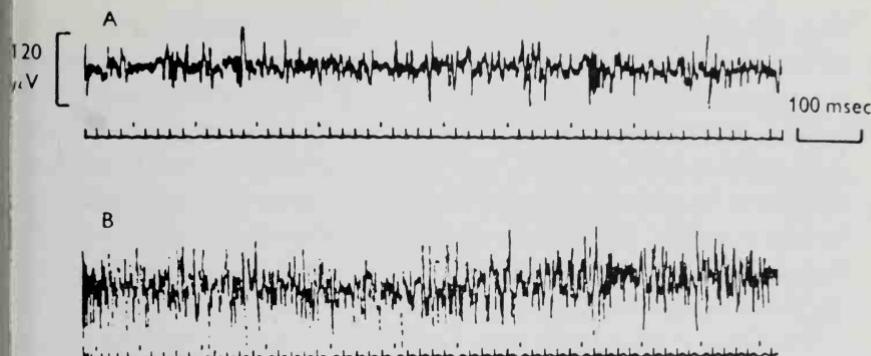
Fig. 109. EMG's of soleus in women. *A*, standing at ease; *B*, standing at ease with high heels. (From Joseph and Nightingale, 1956.)

(1950) who first drew special attention to the intermittent, unconscious, back-and-forth swaying which causes it.

Ferraz, de Moraes and Parolari (1958) have concluded from a study of seven subjects that the peroneus longus and peroneus brevis act intermittently as postural muscles, becoming very active in leaning forward and silent when leaning backward. Their activity is pronounced during the propulsive phase of normal walking, and the activity of the two muscles is synchronous.

Arch Support of Foot

The mechanism of arch support in the foot remains controversial despite years of investigation. According to one theory, the arches are maintained by the contraction of muscles; according to a second, by the strength of passive tissues; and according to a third, by the combination of both muscles and passive structures.

A century ago, Duchenne stated that by faradization of the peroneus longus in flat-footed children he was always able to produce the progressive formation of a normal plantar arch. Keith, in 1929, concluded that muscles are all-important in the support of the arch and that ligaments come into play only after the muscles have "failed." Morton (1935) disagreed. He concluded that the structural stability of the foot is not dependent on mus-

cles. He claimed that appreciable muscle exertion is needed only
when the centre of gravity of the body moves beyond the margins
of structural stability, whereas only a slight controlling action
by the muscles is required when the centre remains between those
margins. In 1952, Morton and Fuller further showed that static
strains upon the foot are relatively low in intensity, falling well
within the capabilities of the ligaments. Their calculations showed
that only acute, heavy, but transient forces, such as in the take-
off phase of walking, require the dynamic action of muscles.

Thus the controversy continued and was kept alive by others
including Kaplan and Kaplan (1935) and Lake (1937). In 1941,
R. L. Jones, using the method of palpation in the living and
direct observation in cadavers, concluded that not more than
15 to 20% of the total tension stress on the foot is borne by the
posterior tibial and peroneal muscles. Much the greater part of
this stress is borne by the plantar ligaments of the foot; but the
short plantar muscles, being in an advantageous position, also
contribute to the support.

After World War II, Harris and Beath (1948) concluded from
their extensive survey in the Canadian Army that both passive
supporting structures and muscles are responsible for a normal
arch. They frankly favored the rôle of the passive structures but
admitted the readiness of the muscles to assume a rôle in arch
support. Wood Jones (1949) agreed that maintenance of the nor-
mal arched form of the foot results from the dual control exerted
by the passive elasticity of the ligaments and the active contrac-
tility of muscles. He concluded that the plantar aponeurosis and
plantar tarsal ligaments hold the anterior and posterior pillars
of the arch together and that the actively contracting intrinsic
muscles between the aponeurosis and tarsal ligaments also play
an important part.

From our general electromyographic study of the leg and foot
with needle electrodes, we concluded that the tibialis anterior,
peroneus longus and the intrinsic muscles of the foot play no
important rôle in the normal static support of the long arches of
the foot (Basmajian and Bentzon, 1954). As noted before, many

if not most of these muscles showed inactivity during standing in a relaxed position. This was confirmed in general terms by Smith (1954) who used skin electrodes. Many standard textbooks, however, still overemphasize the part played by muscles in the support of the arches of the foot. For example, Gray's Anatomy (Johnston, Davies and Davies, 1958) states that the tibialis posterior is the most important factor when the foot is bearing weight, and that the peroneus longus, tibialis anterior, flexor hallucis longus, abductor hallucis and flexor digitorum brevis also contribute to the support.

In an attempt to settle the controversy, we have performed a special study of the muscular support of the loaded arch (Basmajian and Stecko, 1963). Because earlier studies ran the risk of confusing the muscle activity required for postural adjustment with that for the support of the arches, the subjects were seated and the leg and foot were loaded artificially in a special apparatus (fig. 110) that provides graded loads of up to 400 pounds (182 kilograms).

Six muscles of particular interest were chosen for this electromyographic study. They were: the tibialis anterior (since by its insertion it would appear to raise the summit of the medial longitudinal arch), the tibialis posterior and the peroneus longus (since by acting together, these two might provide a sling support), and the flexor hallucis longus, abductor hallucis and flexor digitorum brevis (since all three are in a position to act as longitudinal bowstrings). These muscles were studied with our special indwelling fine-wire electrodes, and simultaneous recordings were made with high-gain amplifiers.

The special load-applicator consisted of a lever made from an oak beam, fixed at one end to a heavy frame by a hinge to provide the fulcrum (fig. 110). The bent knee of the subject could be placed under the beam, and by use of leverage, loads of 100, 200 and 400 pounds could be applied through the vertical leg to the foot. These loads were chosen because 100 pounds approximates or exceeds the normal load on each foot in the upright bipedal stance, 200 pounds approximates or exceeds the load on the arch

FIG. 110. Arrangement of a subject with the load applied by leverage and the foot on the adjustable platform (here set in the horizontal position). (From Basmajian and Stecko, 1963.)

in upright unipedal stance, and the 400 pound load is the maxi-
mum that can be applied without extreme discomfort at the knee.
The system provides a convenient method of loading the arches
while eliminating any postural effect that muscles might have
on the leg and foot. To test the influence of various positions of
the foot and ankle, the foot was supported on a specially con-
structed adjustable platform (fig. 110).

In these experiments, all six of the muscles, which are often
considered to be important contributors to arch support, did not
react to loads that actually surpassed those normally applied to
the static plantigrade foot. One hundred pounds elicited little
if any contraction. With loads of 200 pounds applied to one foot,
a small number of the muscles showed some activity, but this
was exceptional and varied with the muscle and the posture of
the foot. The peroneus longus was dramatically quiescent except,
perhaps, when 400 pounds was applied to the inverted foot.
With this load, however, a substantial number of the other
muscles also came into play (fig. 111).

An analysis of the forces on the arch by the method of Steindler
reveals that 400 pounds does not exceed the normal forces im-
posed on the arch in the take-off position of walking. Our earliest
study (Basmajian and Bentzon, 1954) showed a great deal of
activity in the tibialis anterior, peroneus longus and intrinsic
muscles of the foot when the subjects stood on tiptoe. From these
earlier findings and those of the present study, one may conclude
that in the standing-at-ease posture muscle activity is not re-
quired and the muscles are inactive; however, in positions in which
excessive stresses are applied, as in the take-off phase of gait,
the muscles do react. Without any question, the first line of
defense is provided by the passive structures. During activity
the muscles would appear to contribute to the normal maintenance
of the longitudinal arches.

This brings us back to the conclusion of Harris and Beath that
the normal foot is supported both by passive factors (bones and
ligaments) and by active factors (muscles) and that these factors
are reciprocal. They stated that, in the average or strong foot,
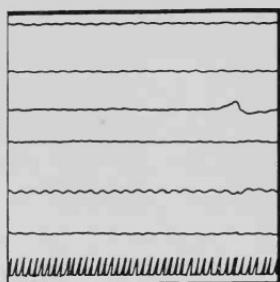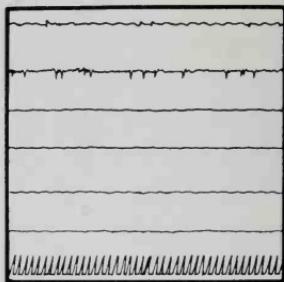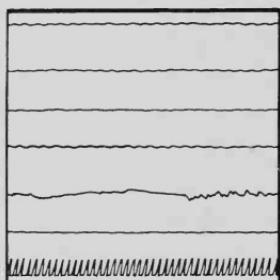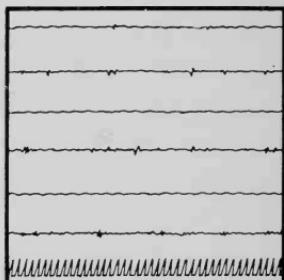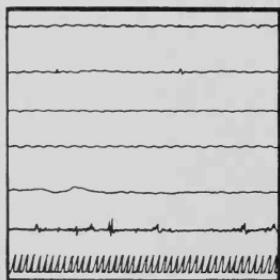
Fig. 111. Sample tracings of electromyographic recordings while the foot is on the horizontal platform to show range of activity from minimum (left side) to maximum (right side) activity with loads of 100, 200 and 400 pounds. T.A., T.P., P.L., F.H.L., A.H. and F.D.B. are abbreviations for tibialis anterior and posterior, peroneus longus, flexor hallucis longus, abductor hallucis and flexor digitorum brevis. T. is the time signal with a frequency of 100 cycles per second and an amplitude of 200 microvolts. (From Basmajian and Stecko, 1963.)

most of the support is provided by passive factors, little load being supported by the muscles. Much greater stability and strength for the foot can be provided by the passive support of a well designed skeleton than from the active support provided by muscles. However, they concluded that the muscles always play some part in maintaining balance and in supporting the load. This latter opinion is shown by the present experiments to be incorrect for the static foot.

Harris and Beath stated further that the strong foot is one in which the tarsal bones are so articulated with each other that the weight of the body is borne without appreciable movement between them. With a strong foot, the muscles are used to maintain balance, to adjust the foot to uneven ground, and, of course, to propel the body in walking and running. The weak foot is one in which the tarsal bones are so shaped and are so disposed that they are unstable and shift in position when weight is superimposed. Only by increasing the support provided by the muscles can the normal shape of the foot be maintained and the body weight supported.

There is a limit to the contribution that muscles can make. They cannot function unremittingly, nor can they provide the powerful support furnished by the skeleton. The first line of defense of the arches is ligamentous. The muscles form a dynamic reserve, called upon reflexly by excessive loads including the take-off phase in walking.

It now appears obvious that any statements made with regard to the rôle of muscles in the support of the arches of the weakly disposed foot need further electromyographic confirmation. Undoubtedly, a study of a series of subjects with flat feet, using the techniques of the present research would help to clarify the situation.

Such a study is now under way in our laboratory. In a preliminary study, my colleague, Edwin Gresczyk (1965), after confirming our results in normal persons, found that more than half of the flat-footed subjects had activity in the muscles tested (tibialis anterior, tibialis posterior, peroneus longus and soleus).

He concluded that the use of these muscles as a dynamic reserve in attempting to maintain the arch was real. We are now greatly expanding this study using fine-wire electrodes in tibialis anterior, tibialis posterior, flexor hallucis longus, peroneus longus, abductor hallucis and flexor digitorum brevis. Preliminary findings lend further support to the theory that in the *imbalanced* foot muscular activity does occur, apparently reflexly (Gresczyk and Basmajian, unpublished).

Free Movements of Ankle

Our own studies and those of O'Connell (1958) have confirmed the classical teaching in regard to the importance of tibialis anterior in dorsiflexion of the ankle with the assistance of extensor digitorum longus and extensor hallucis (fig. 112). The peronei are inactive during dorsiflexion but active during plantar flexion. The activity of the peronei seems to be transmitted chiefly to the transverse tarsal joint and not the ankle joint.
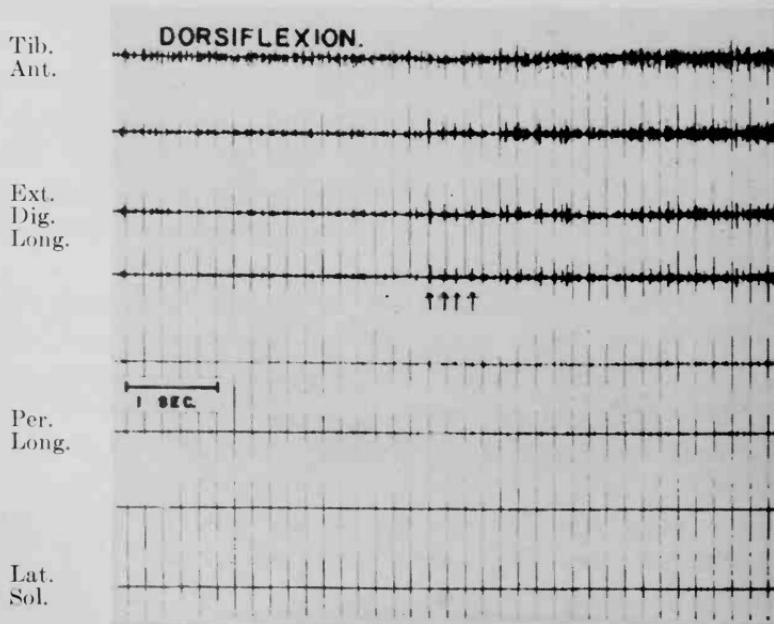
Fig. 112. EMG's of various leg muscles during dorsiflexion. (From O'Connell, 1958.)

O'Connell and I have each found independently that tibialis anterior is not very active in producing inversion *unless dorsiflexion occurs simultaneously*. I have only scattered experiments on the tibialis posterior but these indicate that it is a powerful invertor only when the ankle is simultaneously plantar flexed.

O'Connell proved the lack of a consistent pattern of activity in the two main peronei during eversion, sometimes the one showing activity first and sometimes the other. Moreover, the lateral part of the soleus appeared to become active during eversion while the medial part was active during inversion. This suggests a bipartite behavior of that muscle which requires further investigation. Arienti (1948) has also suggested patterns of activity of different parts of the triceps surae (i.e., gastrocnemius and soleus) during walking on a treadmill rather than unanimity of action. (In the upper limb, we have shown differences in the heads of biceps brachii—Basmajian and Latif, 1957.)

O'Connell and Mortensen (1957) reported on the activity of various muscles of the leg with the limb elevated. The action of tibialis anterior was variable during inversion (which, as seen above, must vary with the concurrent dorsiflexion or plantar flexion of the foot). It was strongly active during forced eversion, a finding which remains unexplained and unconfirmed. One would question this result except for the knowledge of the integrity of the observers.

Houtz and Walsh (1959) compared the activity of the soleus and gastrocnemius in walking and in rising on tip toes. During the "stance phase" of walking, the activity was less in these muscles than in rising on tip toes. In other words, they seem to be stabilizers during walking. Apparently, rising up on the toes is not a normal part of the ordinary gait; this conclusion threatens the hallowed "push-off" concept of walking and might well be correct. Sheffield, Gersten and Mastellone (1956) showed in a simultaneous study of leg muscles during walking that the dorsiflexors (tibialis anterior and the two long extensors of the toes) act in unison during the swing phase, obviously to provide adequate clearance of the ground. Early in the stance phase there is a greater burst of

activity in them, apparently to stabilize the foot on the ground. Sheffield's group appears to have shown that the plantar flexors are stabilizers during the stance phase. They also noted a paradoxical activity in soleus (with none in gastrocnemius) during the swing phase.

Houtz and Fischer (1959) found a surprising amount of activity in tibialis anterior during the pedalling of a bicycle. This must be due to the stabilizing function since the foot is already forced into dorsiflexion by the pedal itself. Gastrocnemius showed considerably less activity than tibialis anterior and, predictably, its occurrence was in the exactly opposite phase of pedalling (see fig. 103 on p. 214).

In an elaborate study of walking, Hirschberg and Nathanson (1952) described the patterns of activity in many of the lower limb muscles. In individuals, a consistent pattern of activity was found. Only one group, the calf muscles, started to contract in the middle of the stance phase, and these were the most active muscles. During the swing phase only the anterior tibial group contracted strongly. Frequently, a burst of activity occurred in gastrocnemius in the middle of the swing phase (see fig. 104 on p. 218). In a brief article, Richter (1966) reported similar findings.

Intrinsic Foot Muscles

Since the first edition of this book a number of new emg studies have been added to our first report (Basmajian and Bentzon, 1954). With needle electrodes, we studied abductor hallucis, flexor digitorum brevis and abductor digiti minimi in 12 men and 2 women. To test the muscles of the foot it was necessary to have the subject stand on a pair of raised blocks with a narrow interval between to accommodate the projecting electrode.

Generally, there was very little activity in these muscles while standing. This has been confirmed by Mann and Inman (1964). Almost all the abductors of the great toe and the short flexors of the toes showed electromyographic silence. A quarter of the abductors of the little toe showed no activity while more than

half showed negligible or doubtful activity. In several cases there was marked activity in abductor hallucis and this was found to be due to "digging in" of the great toe. This activity was more or less abolished immediately when the subject straightened his toe.

When the subjects rose on tip toes there was a marked activity in the intrinsic muscles. This was confirmed in a later study by Oota (1956b). In the take-off stage of walking we found a similar marked activity and this was confirmed by Sheffield, Gersten and Mastellone (1956). (See also p. 153.)

There was no consistent significant relationship between the types of feet and the types of activity in any muscle. However, Mann and Inman found that the pronated foot requires greater intrinsic muscle activity than does the normal foot, "to stabilize the transverse tarsal and subtalar joints."

As suggested before, it now seems to be beyond controversy that tibialis anterior, peroneus longus and the intrinsic muscles of the foot play no important active rôle in the normal static support of the long arches of the foot. Our figures show that these muscles are completely inactive electromyographically in many normal individuals while standing. Furthermore, when a subject suddenly lowers himself rapidly from a raised seated position to a direct relaxed standing position, there is little or no appearance of activity. However, voluntary and visible efforts to increase the arch of the foot is accompanied by marked activity.

Mann and Inman (1964) in their excellent detailed study showed that the intrinsic muscles of the foot act as a group in many movements, especially the abductors of the great and little toes, the flexor hallucis and the flexor digitorum brevis. During walking on the level, they become active at or about the 35% mark of the whole walking cycle (fig. 113). (But activity is earlier with flat footed subjects.) Activity always ceases just before toe-off. When walking on a downslope, the start of activity again is advanced, often occurring from the onset of the cycle (as the heel strikes). Mann and Inman relate the activity in intrinsic muscles to the progressive supination at the subtalar joint. They believe that an important rôle of the intrinsic muscles is the sta-
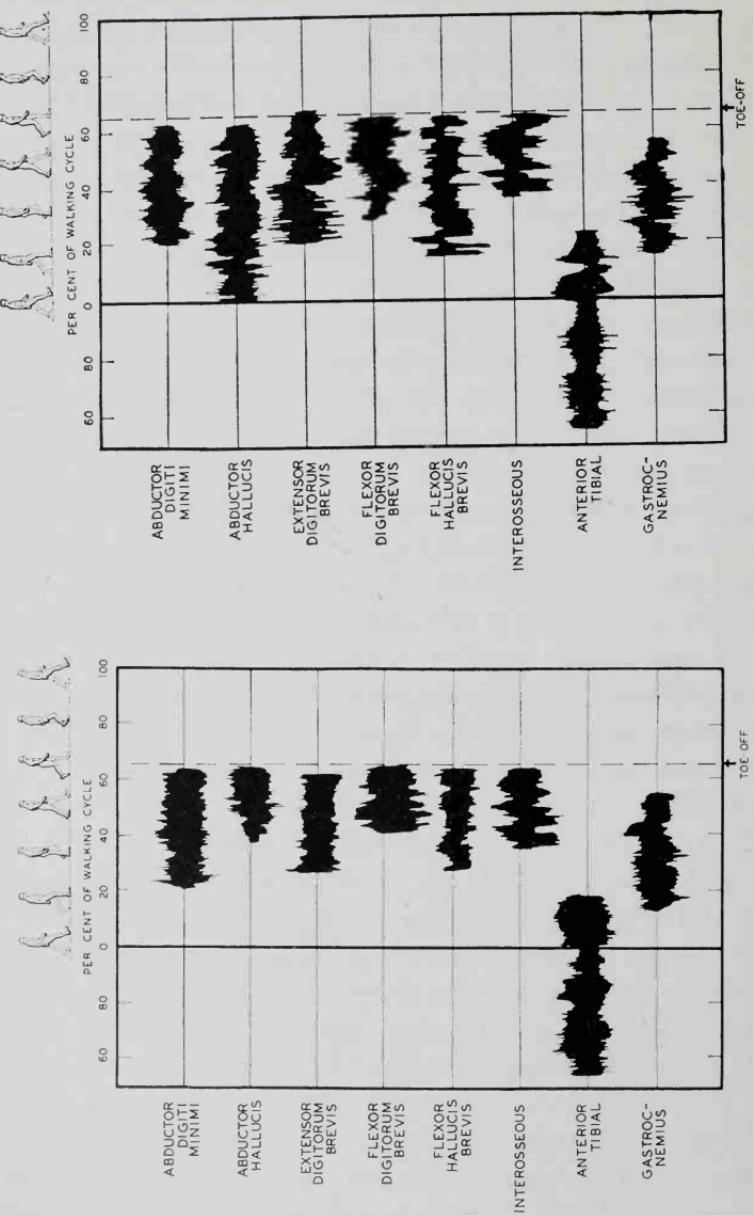
Fig. 113. Cycle of emg activity during walking in muscles of the leg and foot. *Left*, normal; *right*, flat-footed subject. (From Mann and Inman, 1964.)

bilization of the foot during propulsion, acting mainly at the subtalar and transverse tarsal joints. The pronated foot requires greater intrinsic muscle activity than does the normal foot.

Mann and Inman agree with us (Basmajian and Bentzon, 1954) that activity is not needed to support the arches of the fully loaded foot at rest. To fully investigate this, we investigated loading of the static foot while completely removing the factor of posture (Basmajian and Stecko, 1963); see above (p. 231).

Morphology of Abductor Hallucis

For many years, the exact action or function of abductor hallucis has intrigued anatomists and surgeons concerned with deformities of the great toe. Stuart Thomson (1960) of the Sick Children's Hospital in Toronto has found it to be overactive in many cases of hallux varus. Normally, the muscle appears to be important for its stabilizing action rather than for the movements it produces with the foot raised off the ground. In an unpublished morphological study, J. W. Kerr and I made the following observations on 22 adult feet. These feet were dissected with particular emphasis on the insertion of the abductor hallucis muscle.

A great variation in the mode of insertion of the abductor hallucis tendon was revealed. In only one of the specimens did the tendon lie on the medial border of the foot and insert into the medial side of the base of the proximal phalanx in such a fashion as to be an obvious abductor.

At the other end of the scale, in several specimens the abductor hallucis and medial head of the flexor brevis had a common insertion into the base of the medial sesamoid, with the abductor tendon lying on the plantar aspect of the foot as an obvious flexor.

Between these two extremes, we found that in some specimens the abductor tendon was on the plantar aspect of the foot and, passing over the medial portion of the sesamoid without attachment, it inserted into the base of the proximal phalanx. In a quarter of the cases, a slip of insertion was given off the lateral side of the abductor to the medial sesamoid before its insertion on the

phalanx. In another quarter, there was a common slip of insertion with the medial head of the short flexor into the sesamoid.

We concluded that in about one-fifth of our specimens the abductor hallucis was so placed as to be capable of true abduction. In most, the abductor must have acted at the metatarsophalangeal joint to flex the great toe. The abductor hallucis was always closely attached to the capsule of the metatarsophalangeal joint as it crossed it.

Great variation in the attachment of the medial head of the flexor brevis to the abductor tendon was found. In every case, there was an attachment between the two muscles proximal to the sesamoid. The insertion of the medial head of the short flexor was always into the ventral surface of the abductor hallucis tendon.

The Plantar Reflex

Landau and Clare (1959) analyzed the normal and abnormal plantar reflex (Babinski sign) electromyographically. The flexor response shows variable patterns of muscle contraction, while the abnormal extensor response shows both hyperexcitability and stereotypy. The unique feature of the abnormal extensor response is the recruitment of anterior crural muscles—extensor hallucis longus, tibialis anterior and extensor digitorum longus. Then there is an actual mechanical competition between the flexors and extensors of the great toe and it is the latter that triumph. If, perchance, the extensors are weak or denervated, flexion occurs when the Babinski extensor sign would be expected. Thus Landau and Clare concluded that the extensor reflex is really just a hyperactive flexor response with radiation to the extensors which, proving stronger as a rule, produce extension of the great toe (see fig. 50 on p. 92). However, caution must be exercised in accepting this conclusion, for Grimby (1963b) has shown that the plantar response is a complex phenomenon and not a simple reflex. It depends to a great deal on the exact area of skin stimulated (Grimby, 1963a; Engberg, 1964).

The Back

ALTHOUGH others have studied the intrinsic muscles of the back, no names are better known in this field than those of Floyd (a physiologist) and Silver (an anatomist) of Middlesex Hospital Medical School in London. During the 1950's these two investigators broadened our understanding of the erector spinae, and this chapter will lean heavily on their reports. Further detailed studies are called for because the regional or local differences in the structure and function of the many muscles in this group must be explained. Furthermore, clinical conditions exist—the most important of which being scoliosis—that demand clarification. The tentative effort of Riddle and Roaf (1955) was a step in the right direction. However, their conclusion that deep rotator muscle paralysis is the cause of idiopathic scoliosis cannot be substantiated by their published findings, though it may well be the truth (Basmajian, 1955b). Żuk (1960, 1962a, 1962b) of Warsaw demonstrated increased muscular activity on the convex side of the scoliotic curve. He believed it to be a secondary reaction of the body in an attempt to compensate for the curvature, the cause of which he blamed on "muscle imbalance." His series of patients examined electrically numbered some 250.

Turning to the emg studies of the normal back, we must observe the early work of Lewer Allen in South Africa. In 1948, he reported a study with the emphasis on erector spinae. His chief conclusion was that the erector spinae is active during forward flexion of the vertebral column. Therefore, one main function is to control "paying out," which, in this muscle, is as important as the function of extension (fig. 114).

In very rapid flexion, little or no activity is required or in fact appears. As the slowly flexing trunk is lowered, the activity in erector spinae increases apace and then decreases to quiescence when full flexion is reached. If an attempt is made then to force flexion further, silence continues to prevail in the erector. In full flexion, then, the weight of the torso is borne by the posterior ligaments and fasciae—the posterior common ligament, the ligamentum flavum, the interspinous ligaments and the thick dorsal aponeurosis. The erector spinae again comes into action when the trunk is raised once more to the erect position.

In standing erect, Lewer Allen believed that activity in the erector spinae is not required except for forced extension. He seems to have concluded in this admittedly early and not completely elegant study that no activity in the erector spinae results during extension except with added resistance. This is a dubious conclusion which has never been either explained or confirmed.

Soon after, Floyd and Silver (1950) confirmed the main finding of Lewer Allen. They pointed out that Fick (1911), without the benefits of electromyography, had hypothesized the complete relaxation of the erector spinae in full flexion of the spine. Their experiments were, on the whole, more elegant than any others done on this part of the body. With multiple surface electrodes on the skin over the muscle at the levels of T 10 and 12 and L 2 and 4 and the added use of needle electrodes for confirmation, they were able to show the activity of multifidus as well as erector spinae (fig. 115).

Their findings showed that in the initial stages of flexion of the trunk in bending forward the movement is controlled by the intrinsic muscles of the back. They agreed with Lewer Allen that
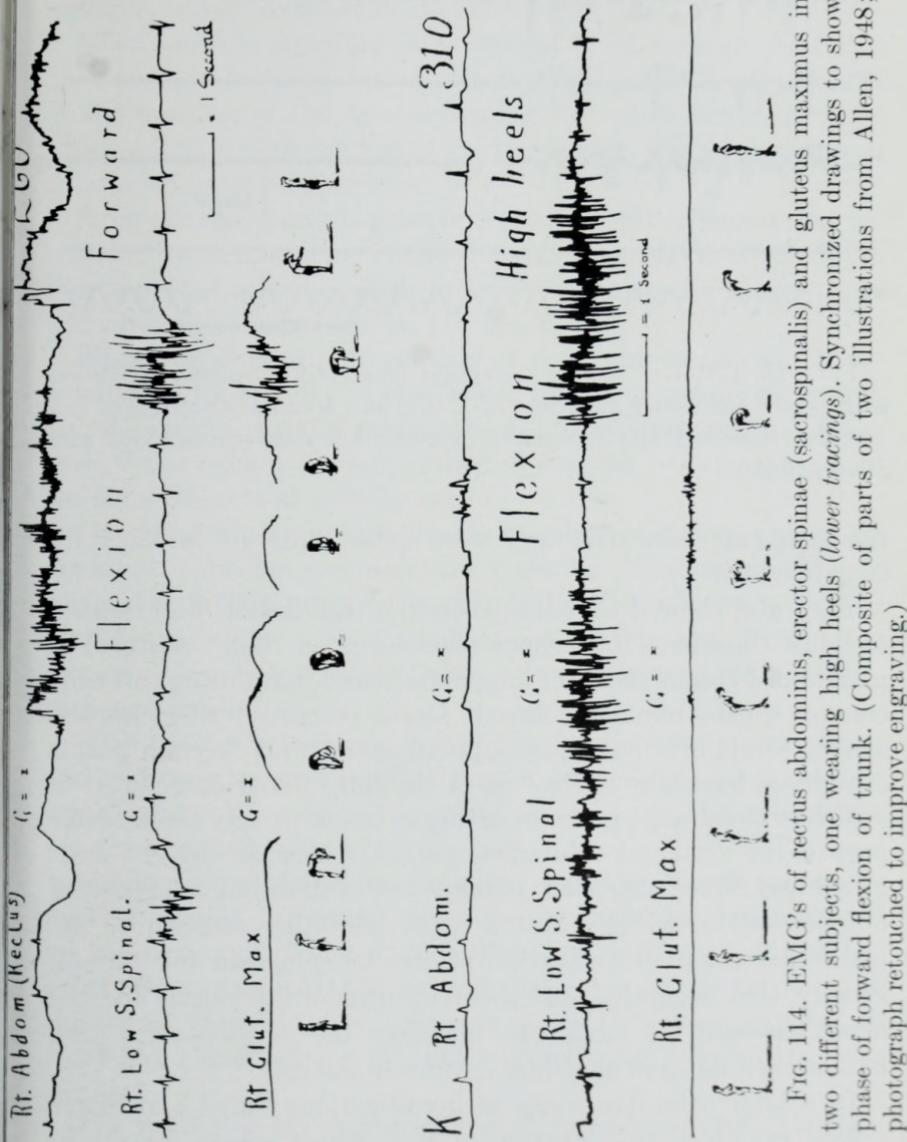
FIG. 114. EMG's of rectus abdominis, erector spinae (sacrospinalis) and gluteus maximus in two different subjects, one wearing high heels (*lower tracings*). Synchronized drawings to show phase of forward flexion of trunk. (Composite of parts of two illustrations from Allen, 1948; photograph retouched to improve engraving.)
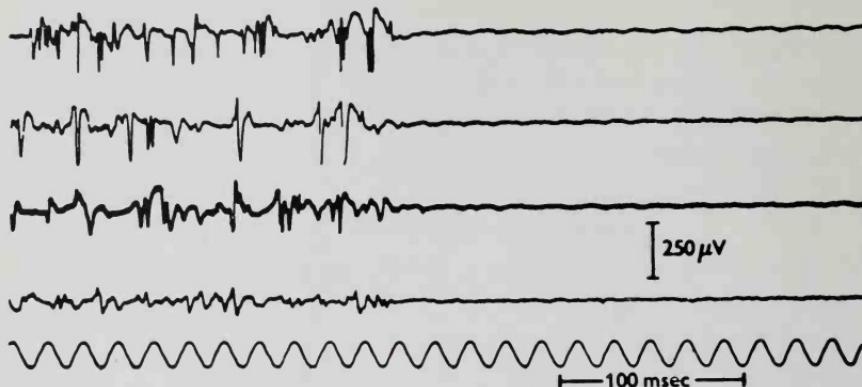
FIG. 115. EMG of flexion-relaxation of erectores spinae. Recorded with needle electrodes at depths of 1, 2, 3 and 4 cm, at the level of L 3 vertebra. Similar EMG's were obtained at all depths. (From Floyd and Silver, 1955.)

the ligaments take over and were quite sufficient in the fully flexed position.

They also showed that the position of full flexion while seated (usually considered by school teachers as a "bad" posture) is maintained comfortably for long periods and that during this time erector spinae remains relaxed. Quite correctly, they warned against jumping to conclusions, pointing out that "certain people experience backache if they sit in the fully flexed position for a sufficient time—e.g., patients sitting in bed with only the thoracic part of the vertebral column supported, motor-car drivers, etc." Floyd and Silver suggested, perhaps too cautiously in the light of our present knowledge, that a reflex inhibitory mechanism explains the complete relaxation of erector spinae in full flexion. Finally, they suggested that this relaxation of the muscle and the dependence on the ligaments, including the intervertebral disc, had implicit dangers including injuries to the disc.

In a later extensive series of investigations Floyd and Silver (1955) examined the function of the erector spinae in certain postures and movements and during weight-lifting. They used both surface and confirmatory needle electrodes for the thoraco-

lumbar parts of the erector spinae. Posture was recorded by photography, direct measurements and radiography.

Most subjects standing in a relaxed erect posture showed a "low level of discharge" in the erector spinae. Small adjustments of the position of the head, shoulders or hands could be made which would abolish the activity of the muscle, i.e., an equilibrium or balance could be achieved.

From the easy upright posture, Floyd and Silver found that extension (hyperextension) of the trunk is initiated, as a rule, by a short burst of activity. Their findings during flexion of the trunk were described before (see p. 154 and fig. 77).

While standing upright, flexion of the trunk to one side is accompanied by activity of the erector spinae of the opposite side, i.e., the muscle is not a prime mover, but an "antagonist." However, if the back is already arched in extension (hyperextension) not even this sort of activity occurs.

Floyd and Silver state that erectores spinae contract (apparently vigorously) during coughing and straining. This occurs even in the midst of their normal silence whether the subject is erect or "full-flexed." The clinical implications of this last observation have not been, in my point of view, adequately explored by orthopedic specialists.

With the subject standing, the activity in erector spinae ceases earlier during forward bending than it does when he is seated. In some patients they found complete relaxation in the sitting, but not the standing posture.

Finally, Floyd and Silver reported that the erector spinae remained relaxed during the initial movement of lifting weights of up to 56 pounds. They proved that it is movement at the hip joint that accounts for the earliest phase of apparent extension of the trunk. However, the ligaments of the back were required to carry the added weight without help from the adjacent muscles (fig. 116).

The studies on the erector spinae of Åkerblom (1948), Portnoy and Morin (1956) and of Joseph and McColl (reported by Joseph in his book *Man's Posture*, 1960), are especially concerned with
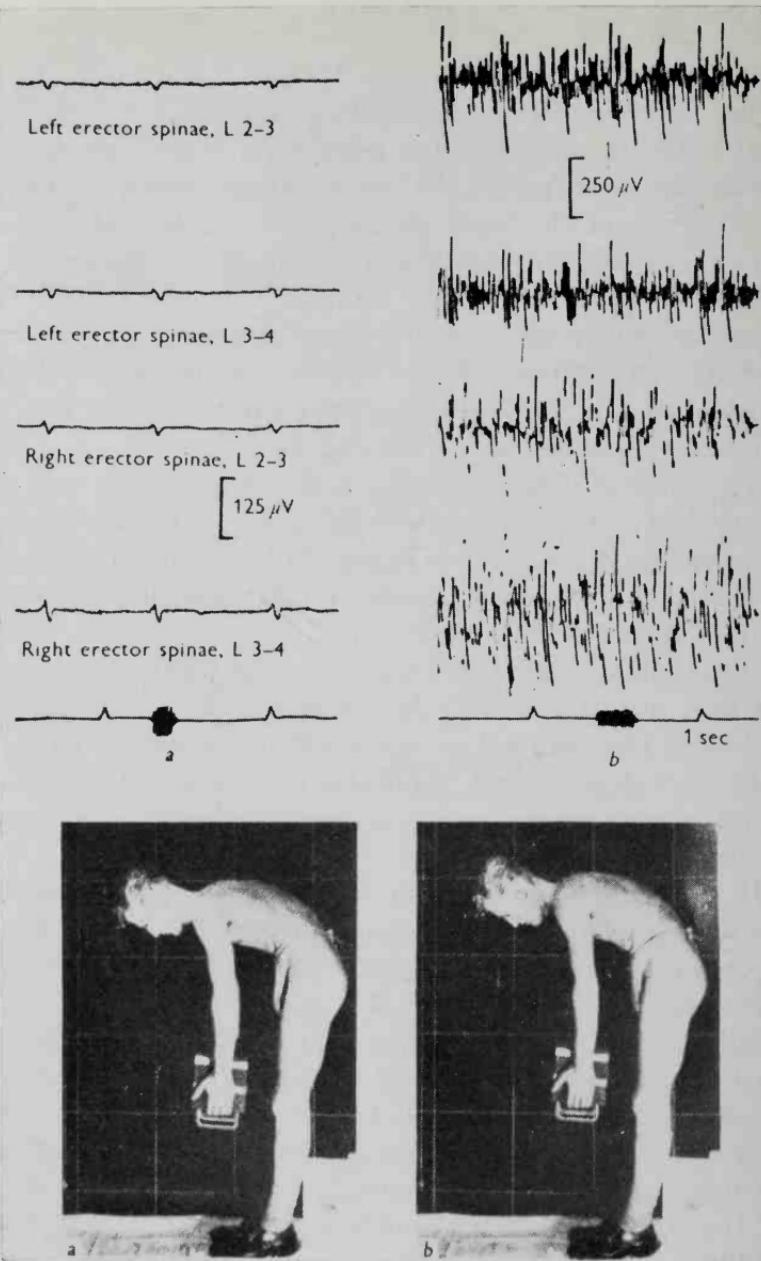
FIG. 116. EMG's of erectores spinae during weight-lifting. Left and right sides at levels L 2 to 3 and L 3 to 4, with corresponding photographs. The subject lifted a 28-lb weight from the ground without activity in erectores spinae until the trunk reached a position intermediate between those shown in photographs. (From Floyd and Silver, 1955.)

posture and are discussed in that chapter on page 154. In essence they agree with Floyd and Silver.

In 1958, Friedebold of Berlin reported a study on the mode of action of erector spinae in a series of women who carried out a series of movements and postures of the trunk. In addition to confirming in general the earlier studies, this report enlarged upon the activity during lateral flexion. Most impressive is the recording of activity from both right and left erectores during bending to either side, though there seems to be a pattern of cooperative activity and not a simple simultaneous antagonism (fig. 117).

A new dimension in the EMG of intrinsic muscles of the back was added by Morris, Benner and Lucas (1962) of San Francisco. They investigated the activity of different layers and parts of the spinal musculature—iliocostalis in the thoracic and lumbar parts, longissimus and rotatores in the region of the 9th and 10th ribs and multifidus abreast of the 5th lumbar spine.

During the performance of various trunk movements, muscles showed patterns of activity that clearly showed two functions—sometimes they initiate movement and at other times they stabilize the trunk. Almost all the movements recruit all the muscles of the back in a variety of patterns, although the predominence of certain muscles is also obvious.

In compound movements, when subjects are not trying to relax, there is constantly more activity than when the movement is carried out deliberately and with conscious effort to avoid unnecessary activity of muscles. Complete relaxation and lower levels of contraction are the "ideal" rather than the rule for normal bending movements. Morris *et al.* found that muscles that might be expected to return the spine to the vertical position often remain quiet; they suggest that such factors as ligaments and passive muscle elasticity play an important role.

During easy standing, *longissimus* is slightly to moderately active; it can be relaxed by gentle ("relaxed") extension of the spine. During forced full extension, flexion, lateral flexion and rotation in different positions of the trunk, it is almost always prominently active.
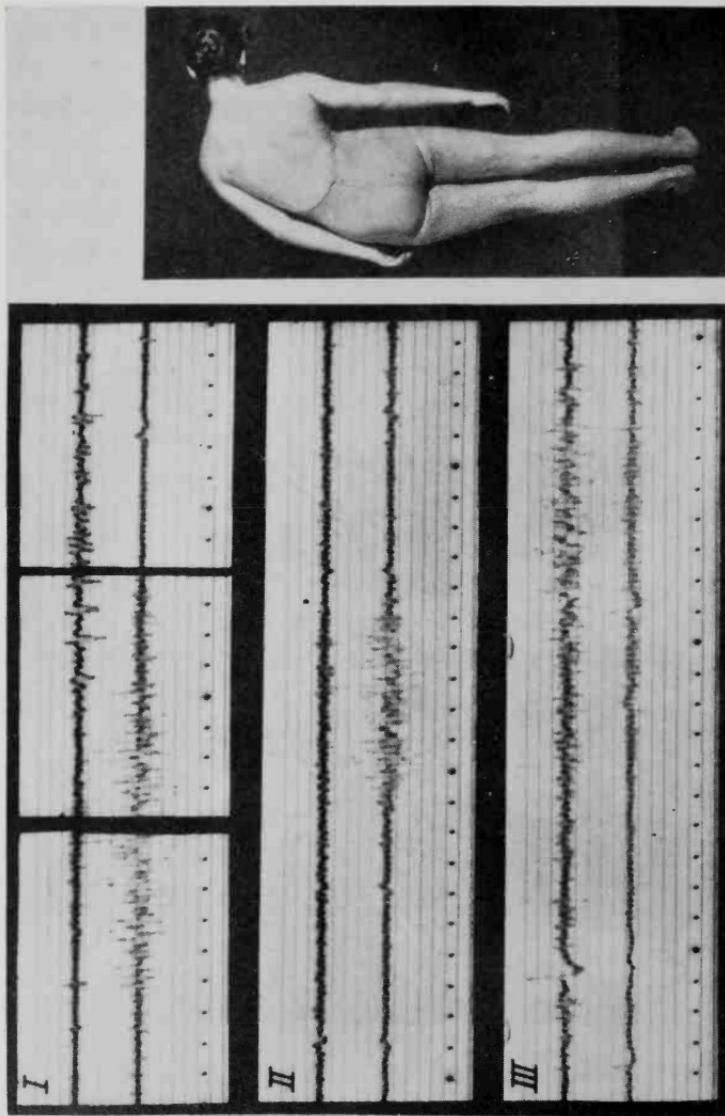
FIG. 117. EMG's of right and left erectores spinae during lateral bending. *I*, upper lumbar region; *II*, middle lumbar region and *III*, corresponding points at both levels reciprocally. (Surface electrodes used, but are not shown.) (From Friedebold, 1958.)

A position of complete silence is easily found for *iliocostalis* in the erect position, but with slight forward swaying activity is instantly recruited. Forward flexion and rotation in the flexed position bring out its strongest contractions; but it is also fairly active in most movements of the spine.

Multifidus and rotatores have rather similar but not identical activity. With movements in the sagittal plane, they are active as they also are in contralateral rotary movements. Yet like all the other muscles, these too relax almost completely during full flexion, leaving the trunk practically hanging on its ligaments.

More recently, Pauly (1966) of Tulane University (New Orleans) has conducted a systematic exploration of the intrinsic muscle of the spinal column during various exercises widely advocated for physical fitness. At the same time he has clearly confirmed the earlier studies of the back and has revealed new aspects of the normal functioning of these muscles. Unlike some earlier workers, he finds that semispinalis capitis and cervicis apparently help to support the head by continuous activity during upright posture.

In almost all vigorous exercises performed from the orthograde position, Pauly finds that the most active muscle is spinalis; next in order is longissimus, and least is iliocostalis lumborum. Nevertheless all three muscles and the main mass of erector spinae act powerfully during strong arching of the back in the prone posture. During push-ups, there is considerable individual variation, but typically, the lower back muscles remain relaxed.

Simple side-bending exercises of the trunk do not recruit erector spinae so long as there is no concomitant backward or forward bending. This clearly refutes earlier opinions whose authors had ignored movements in the ventro-dorsal plane that do involve erector spinae.

Conclusions

This chapter will be ended by emphasizing what must have become apparent to the informed reader. Electromyography has a

great deal of practical value in this area and, aside from some general—but important—observations recorded above, much remains to be learned by this technique, especially about the fine functioning of various areas and depths of the intrinsic muscles of the back.

CHAPTER *13*

Human Locomotion

O<small>F</small> all the electromyography done in recent years, studies on locomotion give the greatest promise of practical application. Yet the sad fact is that such application is slow in coming. At least one reason for this delay is a lack of synthesis of the various findings. These remain relatively isolated and therefore meaningless to those who might use the information. This chapter will be devoted to an attempt at such a synthesis. Taken with the foregoing chapters on Posture, Limbs and Back, it gathers in one place all that appears to be significant on the use of EMG in studies of human locomotion. Locomotion and gait are not synonymous, but unfortunately no emg research has gone beyond simple walking. Yet the title of this chapter remains what it is in the hope that it will act as a goad for new investigations.

Lower Limb in Gait

Although movements of the trunk and upper limb play a rôle in normal walking (and will be discussed at the end of the chapter), the activity of the lower limbs evoke the greatest interest. A number of laboratories have devoted many years of study to the movements of the joints and accompanying muscular activity.

Prominent among them is the Biomechanics Laboratory in the University of California at San Francisco, which has conducted a long series of studies since 1944. The early investigations there dealt with the problems of amputees, and they are quite unique. Normal body mechanics and gait have occupied a greater part of the Laboratory's time in the past decade. Particularly useful, but outside the scope of the present review, are other California studies on the energy cost of various types of gait (reviewed by Ralston, 1964). The emg studies of Liberson and the biomechanical studies of Elftman are also especially important and will be drawn upon below.

In any study of gait, EMG by itself would be of limited value. If quantitative evaluations are to be made, it must be supplemented with other biomechanical techniques. Photographic methods, particularly high-frequency cinematography, have been used since the classic studies of Muybridge (1887). Marey (1885) in France, Braune and Fischer (1895) in Germany, and Bernstein (1935, 1940) in Russia, all greatly improved the techniques of photographic cyclograms. Liberson (1936) was the first to combine these methods with electronic accelerometers while Schwartz, Trautman and Heath (1936) introduced the recording of contacts of various parts of the foot with the ground (with an instrument called an electrobasograph). This later led to the use of walking on force-plates in which multiple, electronic, force and displacement transducers are incorporated. The latter technique has been used intensively in several centres, but its expensiveness in equipment and time has proved forbidding for most laboratories. Nevertheless, Carlsöö (1962) has designed a fairly simple apparatus, as has the group at Purdue University (Ismail *et al.*, 1965).

In general, accelerometers appear to offer easier solutions. Combined with multichannel EMG in early studies at our laboratory, they are giving promising results. At this time, however, Liberson and his colleagues (1962, 1965) of Chicago have the longest and most fruitful experience with accelerographs applied to gait.

The results of the San Francisco studies led Saunders, Inman and Eberhart (1953) to define the six major determinants of

human gait as: (1) pelvic rotation, (2) pelvic tilt, (3) knee flexion, (4) hip flexion, (5) knee and ankle interaction and (6) lateral pelvic displacement. Actually, the phenomenon of walking is much more complex; yet these are the components that provide the unifying principles. Locomotion is "the translation of the center of gravity through space along a path requiring the least expenditure of energy." Pathological gait "may be viewed as an attempt to preserve as low a level of energy consumption as possible by exaggerations of the motions at the unaffected levels." When a person loses one determinant from the above six, compensation is reasonably effective. Loss of the determinant at the knee proves the most costly, according to Saunders *et al.* Loss of two determinants makes effective compensation impossible; the cost in terms of energy consumption triples and apparently discourages the patient to the point of his admitting defeat.

Phases in Walking Cycle

Traditionally, human gait is composed of two phases: (1) stance, beginning when the heel strikes the ground, and (2) swing, beginning with toeing-off. Radcliffe's (1962) diagram (fig. 118) illustrates the interaction between the knee and ankle joints and the phasic action of the major muscle groups recorded electromyographically. (The terms "knee moment" and "ankle moment" refer to the action of muscles about the knee or ankle which tend to change the angle of these joints towards either flexion or extension.)

In figure 118, one should not miss the following features:

As the heel strikes the ground the hamstrings and pretibial muscles reach their peak of activity.

Thereafter, the quadriceps increases in activity as the torso is carried forward over the limb, apparently in maintaining knee stability.

At heel-off the calf group of muscles build up a crescendo of activity which ceases with the toe-off. Before and during toe-off, quadriceps and sometimes the hamstrings reach another (but smaller) peak of activity.
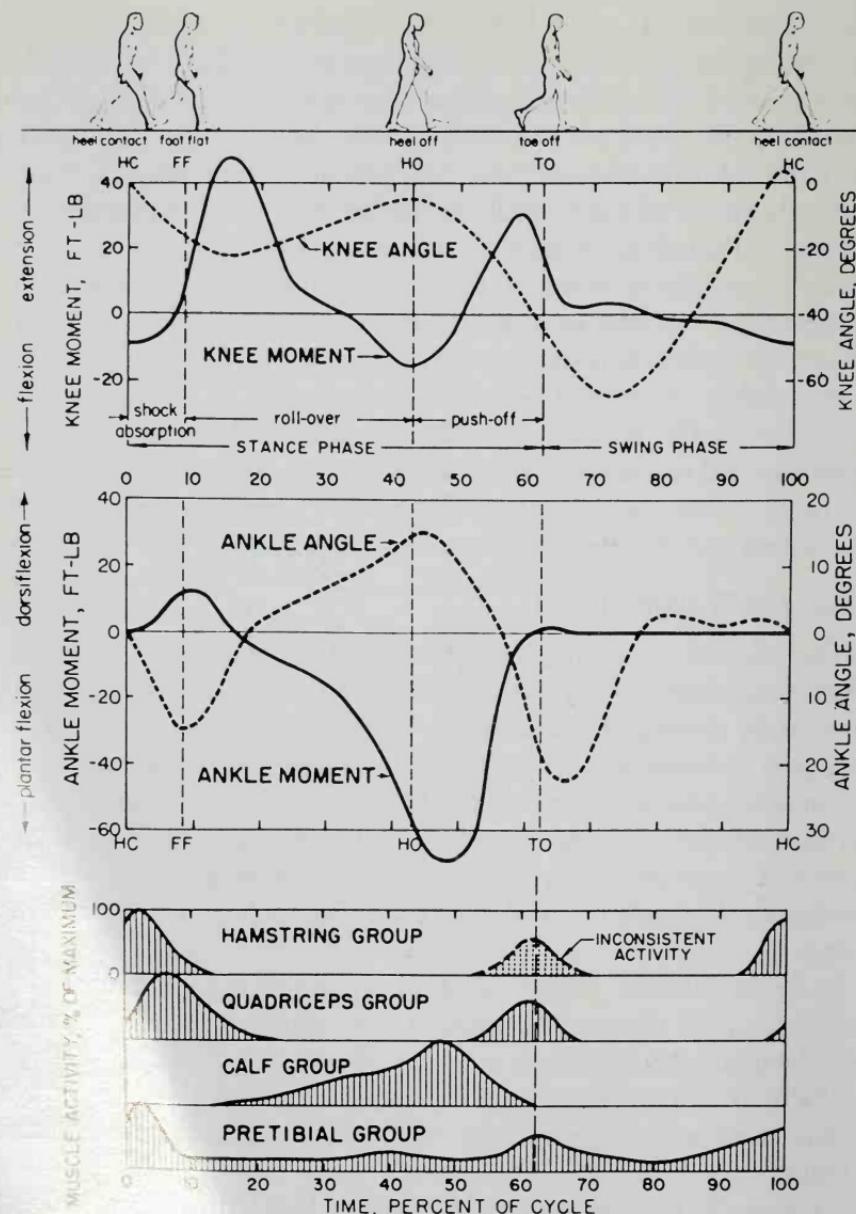
Fig. 118. Normal walking: knee and ankle moments (in foot-pounds) compared with muscular activity during one cycle of walking (right heel to right heel contact) on level ground. (From Radcliffe, 1962.)

The pretibial muscles maintain some activity all through the cycle, rising to a peak at heel-contact and a smaller peak at toe-off.

The complex phasing of these normal actions has led the San Francisco investigators to studies of amputees and prostheses (Radcliffe, 1962). Similar work on the muscle functions in lower amputees is in progress in Poland under the direction of J. Tomaszewska (1964) of Poznan, and M. Weiss (1959, 1966) of Warsaw. There is little doubt that all such work will stimulate improvements in prosthetic appliances of both the conventional and myoelectrically-controlled types.

In a recent review, Elftman (1966), a pioneer in the multifactorial approach for the study of gait, gives the apt warning that electromyography requires the addition of other criteria for the monitoring of tension in non-isometric contractions. Studies of the calf and foot during walking have in the past two decades employed such adjuncts with notable success. Eberhart, Inman and Bresler (1954) showed that the function of the calf muscles during walking is limited to the push-off. They lift the body against gravity on the forepart of the foot.

Radcliffe (1962) postulated that during the stance phase the stabilizing function of the ankle plantar-flexors at the knee is most important. This was confirmed by Sutherland (1966) by means of combined EMG's and motion pictures of gait. The period of activity in the calf muscles and of knee extension and dorsiflexion of the foot corresponded. Only at the end of plantar-flexion of the ankle did plantar-flexion of the foot occur. A bizarre finding was that knee extension occurred after quadriceps activity had ceased. This is related to the fact that full extension of the knee never occurs during walking in the way that it does in standing (Murray et al., 1964).

Sutherland believes that knee extension in the stance phase is brought about by the force of the plantar-flexors of the ankle resisting the dorsiflexion of the ankle; this dorsiflexion is in turn the resultant of extrinsic forces—kinetic forces, gravity and the reaction of the floor. Because the resultant of extrinsic forces proves to be greater, increased dorsiflexion of the foot continues until heel-off begins. The restraining function of the ankle plantar-

flexors in decelerating forward rotation of the tibia on the talus proves to be the key to their stabilizing action.

Using similar techniques, Houtz and Fischer (1961) have produced evidence that a movement of the torso and hip region that shifts their position over the feet initiates the movements of each foot during walking. Movements initiated in the trunk lead automatically to changes in the position of the leg and foot. Houtz and Walsh (1959), by showing that soleus functions to stabilize and adjust the tibia on the talus, gave additional evidence for the view that movements of the ankle during walking occur as a reaction to muscular forces far removed from the foot. (p. 237).

Liberson (1965b), combining the techniques of motion picture photography, accelerograms, electrogoniograms, myograms and EMG's, has reported the following correlation of activity (figs. 119, 120, 121).

1. Contraction of the triceps surae is followed by that of gluteus maximus on the opposite side.

2. Contraction of iliopsoas occurs simultaneously with that of gluteus maximus of the opposite side.

3. Dorsiflexion of the foot begins at the time of maximum acceleration of the lower leg.

4. Extension of the knee begins at the time of maximum velocity of the leg.

5. Contraction of the triceps surae corresponds to the first hump of the vertical accelerogram.

6. Contraction of the gluteus maximus on the opposite side corresponds to the second hump of the vertical accelerogram.

7. In many cases, two-joint muscles show an increase of tension without emg potentials because they act as simple ligaments during the contraction of the antagonists.

In a brief preliminary report, Joseph (1965) described his findings of telemetered EMG's from a number of muscles used in gait. Generally, his findings were similar to those reported in the '40's and '50's by the San Francisco group. In the swing phase, the hamstrings were inactive (even though knee flexion occurred) and the tibialis anterior was also inactive—but only for a brief period. In the supporting phase, activity occurred early in the
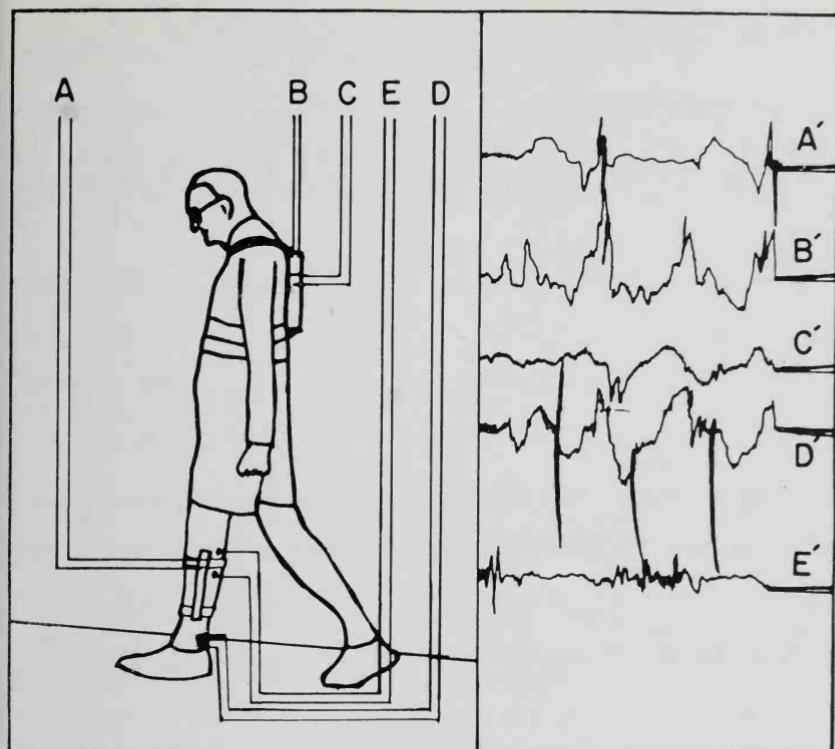
FIG. 119. Diagram of typical multifactorial gait-recording, showing on the left a motion picture frame and on the right oscillograms, the terminal points of which correspond to the instant the picture of the walking subject was taken. A, angular accelerometer on left leg; B and C, vertical and horizontal accelerometers, respectively; D, Lissner strain gauge tensiometer on the left gastrocnemius muscle; E, electrodes in the left gastrocnemius muscle. A', accelerogram of the left leg; B', vertical accelerogram; C', horizontal accelerogram; D', tensiogram from left gastrocnemius muscle; and E', electromyogram from left gastrocnemius muscle. Note that emg activity precedes the major tensiogram deflection and the relationship of the latter to the accelerograms. (From Liberson, 1965b.)

calf muscles, hamstrings and gluteus maximus but ceased toward the end. Two periods of activity were found in the sacrospinalis (at level L 3): one during the swinging and one during the supporting phase.
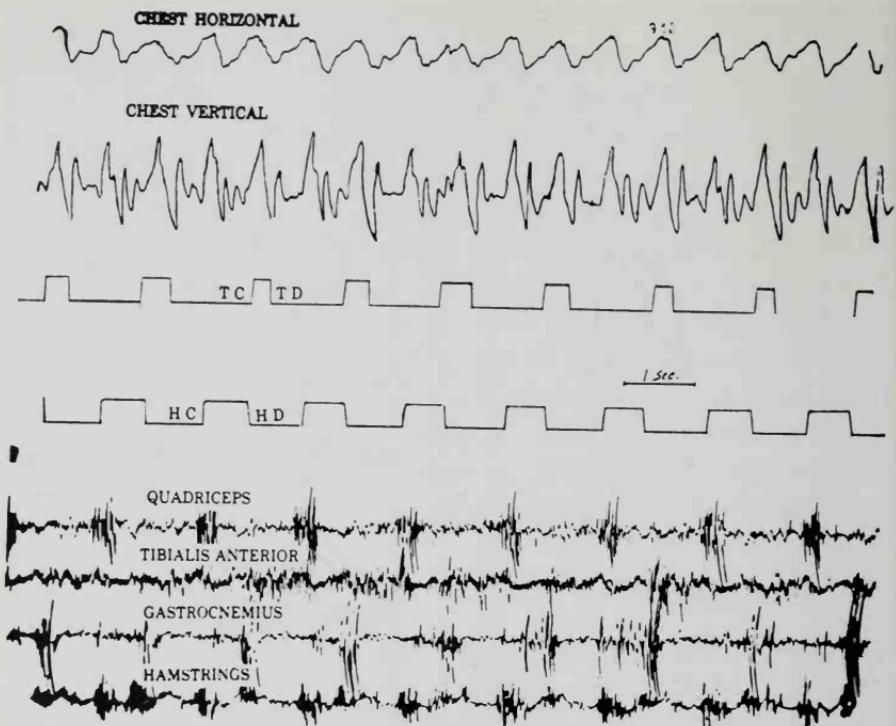
FIG. 120. Series of multifactorial gait-tracings from a normal subject when walking; listed from top down: horizontal and vertical accelerograms; right toe switch (TC, toe contact and TD, toe off); right heel switch (HC, heel strike and HD, heel off); and four electromyograms from muscles in the right lower extremity. (From Liberson, 1965b.)

Later, Battye and Joseph (1966) reported details of a study which, because of its clarity, will be heavily drawn upon below:

In general, they found more similarities than differences in the walking patterns of 14 persons (8 men and 6 women). They also emphasized the importance of the inertial forces as factors in producing certain movements.

Tibialis anterior is usually biphasic in activity, but sometimes it is active for a short time after the foot is flat on the ground— perhaps "to pull the body over the foot in the early part of the supporting phase."

Soleus begins to contract before it lifts the heel from the ground;
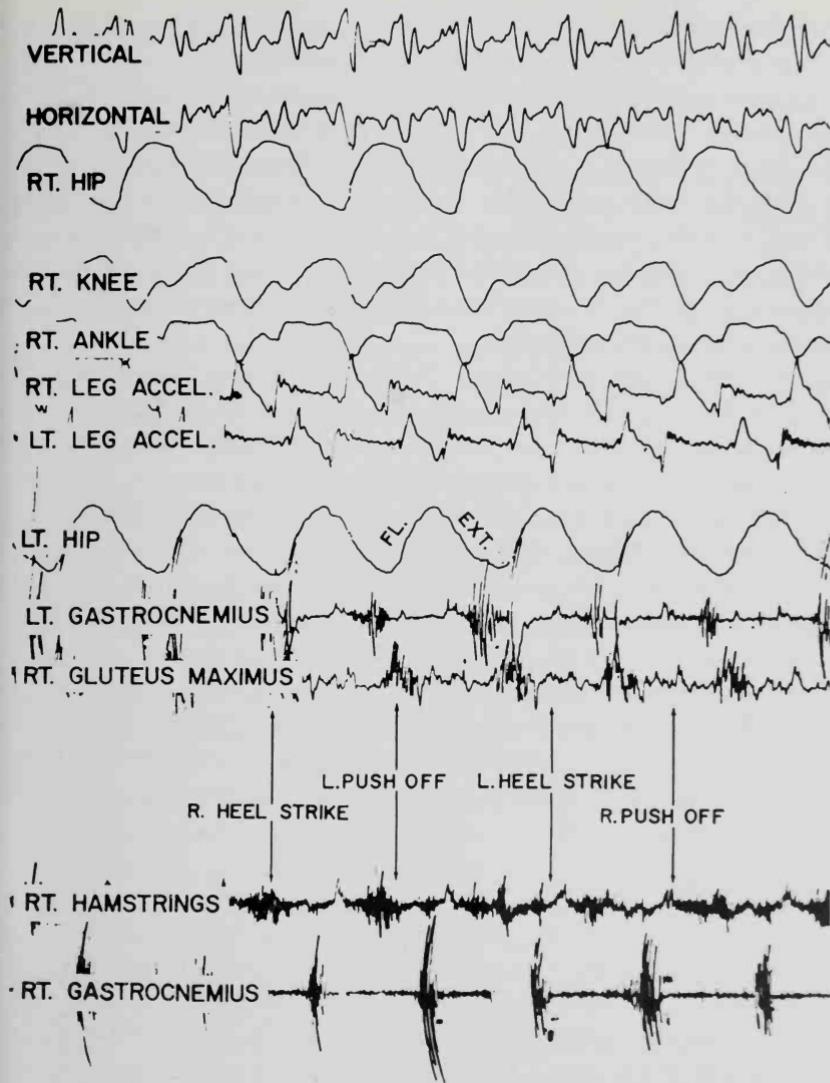
FIG. 121. Series of multifactorial gait-tracings from normal subject during walking, listed from top down: vertical and horizontal accelerograms; goniograms from right hip, knee and ankle; angular accelerograms from right and left legs; left hip goniogram; and electromyograms from left gastrocnemius, right gluteus maximus, right hamstrings and right gastrocnemius muscles. (From Liberson, 1965b.)

it stops before the great toe leaves the ground. Apparently these
are supportive rather than propulsive functions.

Quadriceps femoris contracts as extension of the knee is being
completed, not during the earlier part of extension when the
action is probably a passive swing. Quadriceps continues to act
during the early part of the supporting phase (when the knee is
flexed and the centre of gravity falls behind it). Quadriceps ac-
tivity occurs at the end of the supporting phase to fix the knee in
extension, probably counteracting the tendency toward flexion
imparted by gastrocnemius.

The *hamstrings* contract at the end of flexion and during the
early extension of the thigh apparently to prevent flexion of the
thigh before the heel is on the ground and to assist the movement
of the body over the supporting limb. In some persons, the ham-
strings also contract a second time in the cycle during the end of
the supporting phase; this may prevent hip flexion.

Gluteus medius and *gluteus minimus* are active at the time that
one would predict, i.e., during the supporting phase; however,
some subjects show activity in the swing phase too.

Gluteus maximus shows activity at the end of the swing and at
the beginning of the supporting phase. This is contrary to the
general belief that its activity is not needed for ordinary walking.
Perhaps gluteus maximus contracts to prevent or to control
flexion at the hip joint.

Trunk Muscles During Gait

Erector spinae shows two periods of activity, according to
Battye and Joseph (as noted before by other investigators).
They occur "at intervals of half a stride when the limb is fully
flexed and fully extended at the hip at the beginning and end of
the supporting phase." Battye and Joseph's explanation is that
the bilateral activity of the erectores spinae prevents falling
forward of the body and also rotation and lateral flexion of the
trunk.

Abdominal muscles. Sheffield (1962) found the abdominal
muscles inactive during walking on a horizontal level. Very little

investigation of gait has been done otherwise in this part of the body.

Swinging of the Arm During Gait

Fernandez-Ballesteros, Buchthal and Rosenfalck (1964) of Copenhagen recorded the activity in the arms of normal subjects during walking. Buchthal and Fernandez-Ballesteros (1965) applied the same techniques to a study of patients with Parkinson's disease. The first emg abnormality to appear in the early stages of the disease is a non-rhythmical pattern with random or wrongly timed activity. Later, swinging movements disappear and this becomes quite obvious clinically. In fact, it is characteristic of Parkinson's disease.

In normal persons, the posterior and middle parts of deltoid begin to show activity slightly before the arm starts its backward swing, and this continues throughout the backward swing. The upper part of latissimus dorsi and the teres major act from the onset of the backward swing until the arm reaches the line of the body.

During forward swing of the arm, activity is confined to some of the medial rotators (subscapularis, upper part of latissimus dorsi and teres major); the main flexors are strikingly silent.

In half of their subjects, they found activity in both forward and backward swing in the rhomboids and infraspinatus. This was most marked in persons who walk with a stoop.

Apart for brief silent periods in the extreme positions of swing, trapezius is active in both phases to maintain elevation of the shoulder. Similar activity occurs in supraspinatus; this obviously is related to the prevention of downward dislocation (p. 168). However, Fernandez-Ballesteros et al. ascribe it (unconvincingly) to abduction of the shoulder to allow the arm to bypass the trunk. Trapezius falls silent immediately after a subject comes to a halt, contrary to earlier opinions, but corroborating Bearn's (1961b) finding.
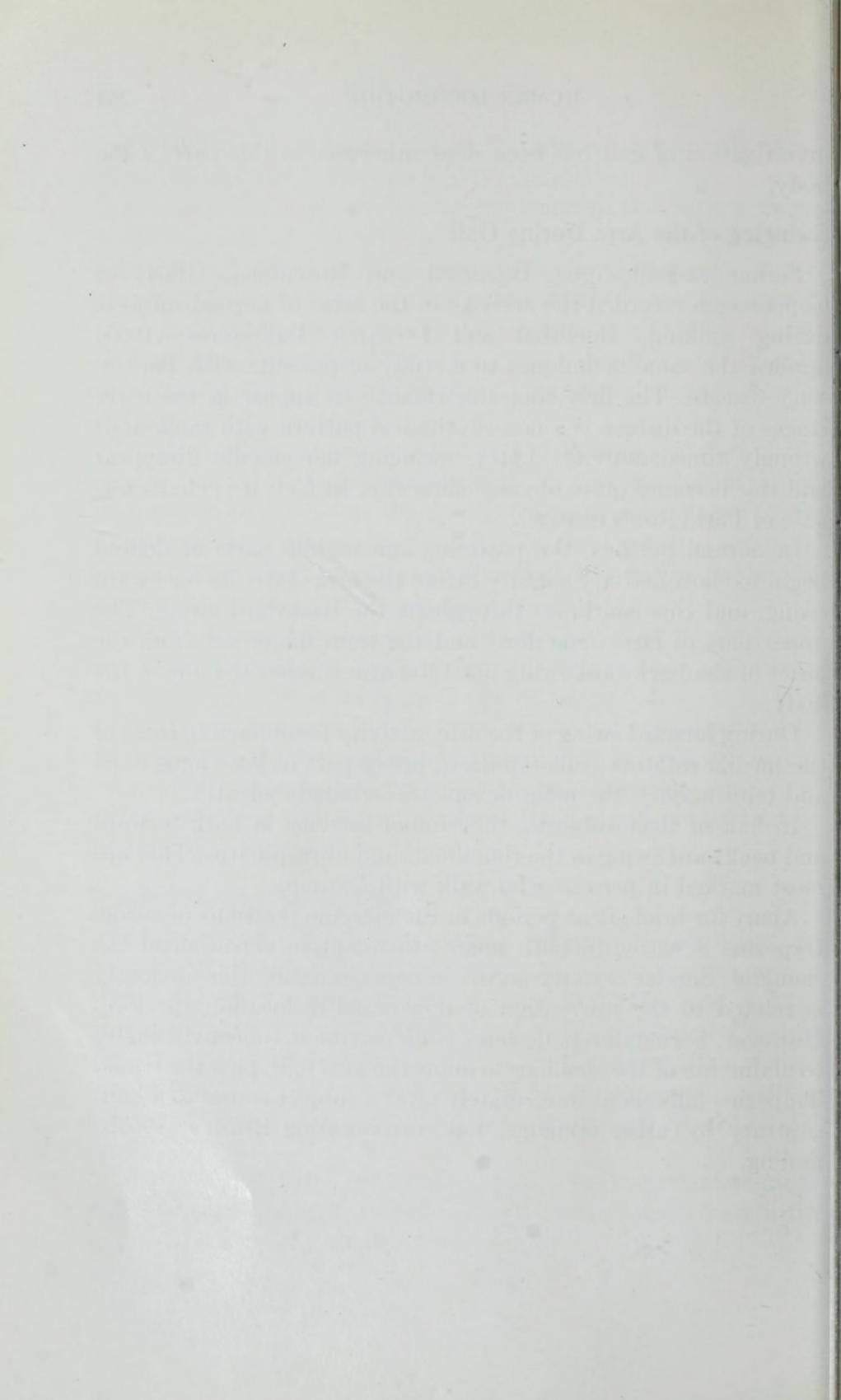
Anterior Abdominal Wall and Perineum

SINCE 1948 a considerable number of papers have appeared which deal with the actions of either specific abdominal muscles, e.g., rectus abdominis, or in connection with specific functions, e.g., posture of the vertebral column or breathing. A few have dealt with the abdominal wall in a more general way and this method of approach will be our first concern. Though I have not published any data concerning the abdominal wall, I have had the occasional opportunity (usually during clinical emg examinations with needle electrodes) of confirming almost all of the systematic observations now to be noted.

Abdominal Wall in General

Floyd and Silver (1950) were the first to make an extensive emg study of the abdominal musculature in normal people. With a grid of paired multiple electrodes on the anterior abdominal wall (fig. 122), they recorded simultaneously from various parts of the rectus abdominis, the external oblique, and the internal ob-
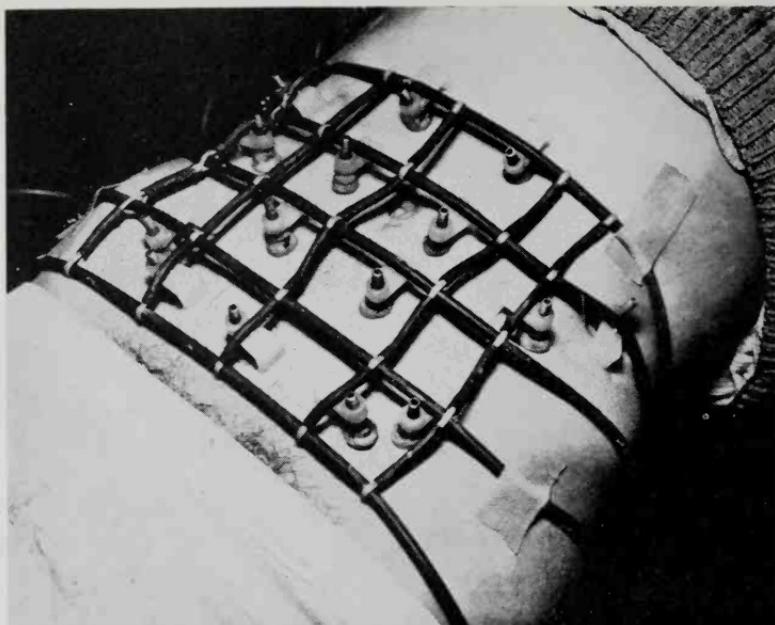
Fig. 122. Photograph from Floyd and Silver, 1950, to show their electrode grid for recording of abdominal EMG's.

lique where it is not covered by external oblique, i.e., in the triangular area bounded by the lateral edge of the rectus sheath, the inguinal ligament and the line joining the anterior superior iliac spine to the umbilicus. Here in this triangle, the external oblique is represented only by its aponeurosis and, quite fortunately, it is this very part of internal oblique which is of greatest interest. (They did not try to study the transversus abdominis because of its depth, admitting the possibility of a pickup from it through the electrodes for internal oblique.)

Floyd and Silver frequently found some difference between the right and left side of the abdominal musculature even when electrodes were carefully matched. They ascribed this to a basic asymmetry in function and found individual variations in the amount of difference.

With the subjects lying supine and resting, slight activity was found in some nervous subjects, but none was found with relaxed
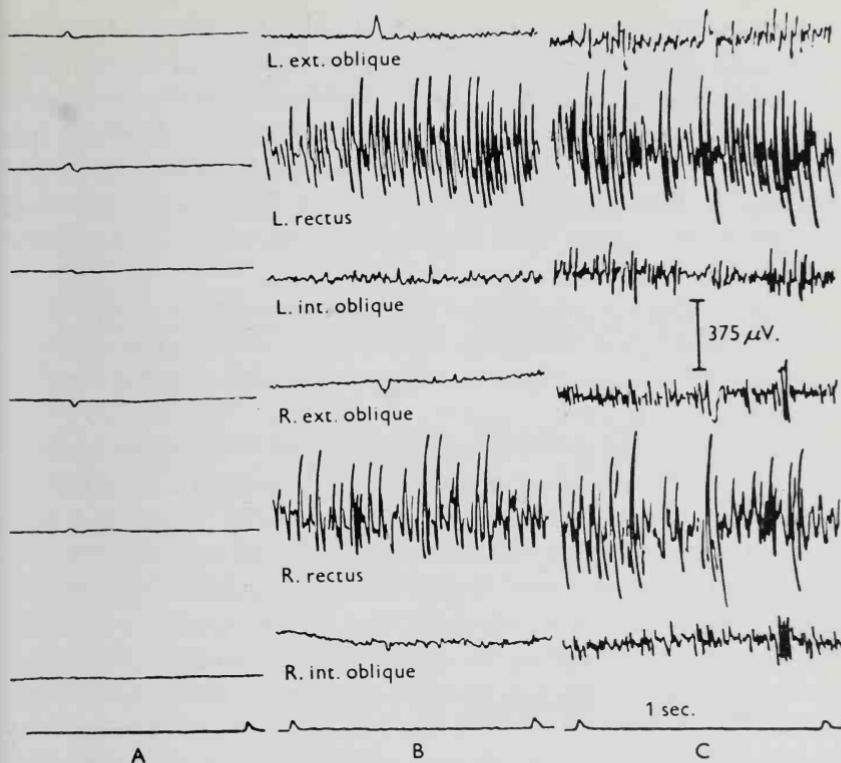
FIG. 123. EMG's of abdominal muscles. *A*, supine; *B*, raising head; *C*, greater effort in head-raising. (From Floyd and Silver, 1950.)

comfortable persons (fig. 123). Even in nervous subjects the activity could be reduced or abolished by proper positioning, e.g., by propping up the upper part of the trunk. Lowering of the trunk caused an exaggeration of activity.

With the "head raising" movement used commonly as an exercise for strengthening abdominal muscles, the recti were powerfully active while external oblique and the part of internal oblique that was studied were only slightly active at first. Even with increased effort they become only moderately active (fig. 123). These findings were confirmed later by Campbell (1952) using needle electrodes, and by Ono (1958) of Hirosaki University. One

might conclude from their finding that only the rectus is benefited maximally by the head raising exercise, in spite of this exercise being advocated to increase the general "tone" of the abdominal wall. In contrast to the head-raising exercise, the bilateral leg-raising exercise brought all the abdominal musculature into activity to steady the pelvis. One-sided leg-raising was much less effective, calling upon activity predominantly on the same side of the abdomen.

In the relaxed standing position, all the electrodes except those over the lower part of the internal oblique picked up no activity. Internal oblique apparently is on constant guard over the inguinal region.

When the subjects (whether recumbent or erect) were made to strain or to "bear down" with the breath held, the external obliques and the internal obliques (lower parts) contracted to a degree that was directly related to the effort; but rectus abdominis, in contrast, was very quiet (fig. 124). This was later confirmed by Ono (1958). Surely it is surprising that physiotherapists have not seized upon these findings for application in the strengthening of weak or stretched obliques. Perhaps they are not dramatic enough!

Floyd and Silver found no inspiratory or expiratory activity in the abdominal muscles during quiet breathing, a finding that was later enlarged upon by Campbell (1952) (see p. 273) and by Ono (1958). With forced expiration, with coughing and with singing, the pattern was similar to that in straining, i.e., marked activity in the obliques and none in the rectus. They emphasized, quite rightly, the importance of the rectus sheath in protecting the abdominal area occupied by the rectus during all these physiological functions which are *not* accompanied by contraction of the rectus. Therefore, they pointed out, repairs of the sheath and maintenance of its integrity during surgical closures is vital. It has been my own experience that surgeons erroneously think hernia is actively prevented by the activity of rectus abdominis in the region it covers. Floyd and Silver have proved conclusively that the apparent hardening of the recti on straining, coughing, etc. is usually only a passive bulging of the muscles and their sheaths.

L. ext. oblique

L. rectus

L. int. oblique

R. ext. oblique

750 μV.

R. rectus

R. int. oblique

1 sec.

A   B
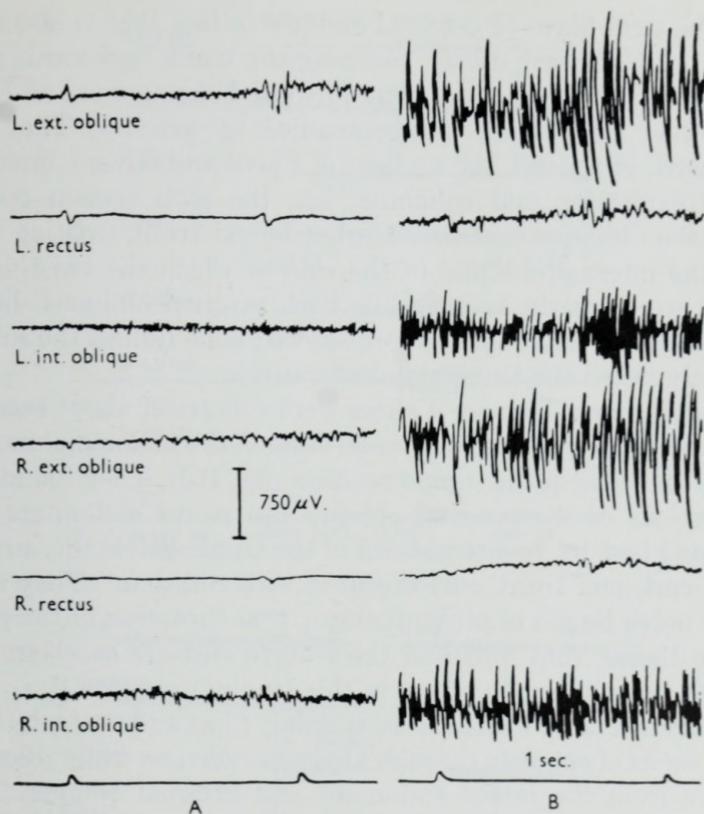
Fig. 124. Abdominal EMG's of "straining." A, during start of straining, and B, 4 seconds later (maximal effort). (From Floyd and Silver, 1950.)

One can only hope that this knowledge, available now for a decade, will soon reach the practising surgeon.

Walters and Partridge in 1957 (then at the University of Illinois) reported on the electromyography of the abdominal muscles during exercise and later added further information (Partridge and Walters, 1959). They found that in movements of the trunk performed without resistance in either the sitting or the standing posture the obliques and recti remained quiescent. However, lateral bending of the trunk does produce activity in the more

posterolateral fibres of external oblique (a fact that is also mentioned by Campbell, 1952). Inclining the trunk backwards gives activity in all the muscles, but forward bending was, as Floyd and Silver also found, unaccompanied by activity. They also confirmed, in general, the findings of Floyd and Silver concerning forced expiration and coughing, i.e., the recti remain relaxed while the obliques contract. During forced trunk-twisting exercises the internal obliques of the side to which the twisting occurred were greatly active while both external obliques showed some slight activity and the recti showed none (unless the subject violently flexed the trunk simultaneously).

Because Partridge and Walters were concerned about exercises in the bedridden patient, they also studied the abdominal muscles during exercises in the supine position (fig. 125). They found that all portions of the external oblique and rectus abdominis were activated best by "a lateral bend of the trunk, pelvic tilt, straight trunk curl, and trunk curl executed with rotation." They state, in the naive jargon of physiotherapy, that "rotation of the pelvis on the thorax (hip roll) and the reverse curl are excellent activators of the internal oblique in this (supine) position."

Concerned more with athletic training, Flint and Gudgell (1965) put a series of subjects through vigorous exercises while recording EMG's from the rectus abdominis and external oblique. Their most effective exercises for bringing out the greatest activity were: the "V-sit," "basket hang" on the horizontal bar, "side-lying trunk raise," backward leaning and "curl-up." (Detailed definitions of these and other technical but explicit terms are given in their article.) Less effective were "chin-up," "pull-up," "pelvic tilt" in the supine position, isometric contraction of the abdominal wall, "low bicycle with pelvic tilt," vertical jumping and straight leg-raising in the supine position. Least effective, to the point of being useless, were "full waist circling" and vertical reach in the standing position, controlled leg extension in the supine position, and "hip-roll" while lying on the mat.

Flint (1965a,b) showed further that the upper and lower parts of the rectus abdominis vary in response to different movements.
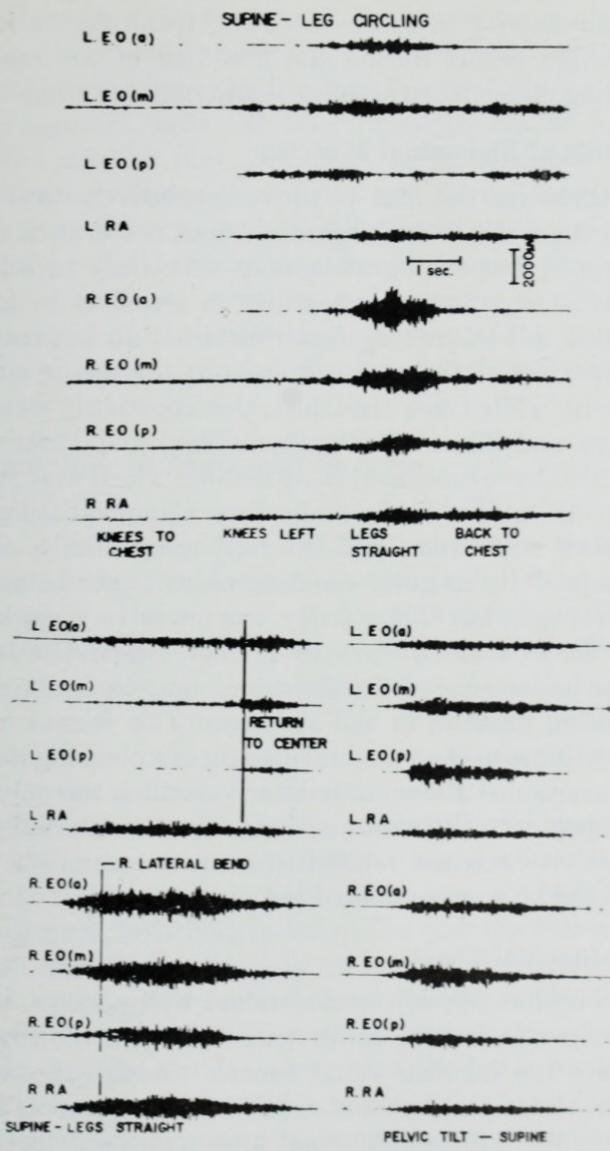
FIG. 125. EMG's of abdominal muscles during various activities while subject supine. (From Partridge and Walters, 1959.)

Most of the activity in the recti during trunk flexion from the supine position occurs during the first half of the movement. Trunk raising elicits more activity than trunk lowering.

Postural Rôle of Abdominal Muscles

Lewer Allen was the first to prove conclusively with electromyography that the rectus abdominis does not draw a resistant spine forwards, but that gravity does this. Only in full-flexion does rectus show activity, apparently in an effort to force the trunk further downwards against resistance. In hyperextension (at the other end of the range of motion) the rectus abdominis shows activity while being stretched; this apparently steadies the torso. Floyd and Silver (1950), Ono (1958) and Partridge and Walters (1959) have confirmed these findings which were predicted many years ago by Duchenne and others. Campbell (1952 *et seq.*) and Campbell and Green (1953 *et seq.*) using needle electrodes found some activity in quiet standing which might be missed by surface electrodes; but this activity was never very marked.

Morris, Lucas and Bresler (1961) and Bearn (1961a) have stressed the importance of the abdominal muscles in the developing of positive pressure in the abdomen. This is said to be an important adjunct to the vertebral column in stabilizing the trunk.

As was mentioned above, in ordinary standing the only muscle to show important continuous activity was the internal oblique, but this activity was not related to maintenance of the general posture; it will be now considered below.

Control of Inguinal Canal

In the consideration of the abdominal wall posture, we must consider in particular the lower part or region of threatening hernia. Here the inguinal canal tunnels through the muscular layers of the abdominal wall and so provides a weak spot. Through this area excessive intra-abdominal pressures (particularly while the person is standing) may force a hernia. Since, in the male, the opening transmits the ductus (or vas) deferens, it must be protected without, however, causing complete occlusion. This

delicate, but dynamic, function is performed by the internal oblique and transversus abdominis—in particular by their lowest fibres which arise from the inguinal ligament. These fibres arch over the inguinal canal and insert medially on the pubic bone. One would imagine that they must be in constant contraction during standing. The work of Floyd and Silver (described above) gives ample evidence to prove this long-held opinion of anatomists and surgeons. Furthermore, one would imagine that, regardless of a person's position, straining and coughing would require increased activity in the muscular protection of the canal. Indeed, the evidence now is overwhelmingly favourable to this view (fig. 124).

Respiratory Rôle of Abdominal Muscles

Following upon the work of Floyd and Silver, their graduate students at Middlesex Hospital Medical School expanded that part which dealt with respiration. Campbell, joined in parts of his research by Green, performed both extensive and intensive studies, combining electromyography of the abdominal muscles and direct and accessory respiratory muscles with various other techniques, such as spirometry. The respiratory muscles will be considered in the next chapter, but here we should consider the findings for the abdominal musculature only.

Campbell's first paper (1952) confirmed and underlined the work of the earlier electromyographers who found that there was no activity in the external oblique and rectus abdominis of supine normal subjects breathing quietly. The new dimension added by Campbell was his use of needle electrodes. He showed that with maximal voluntary expiration these muscles contracted as they also did towards the end of maximal voluntary inspiration (fig. 126). Yet they did not contract under the latter condition when the breathing was increased by imposing asphyxia. In contrast, the activity in maximal expiration was increased further when the volume of breathing was increased by asphyxia.

Campbell reported that the great activity during expiration with hyperpnea appeared first towards the end; it was never
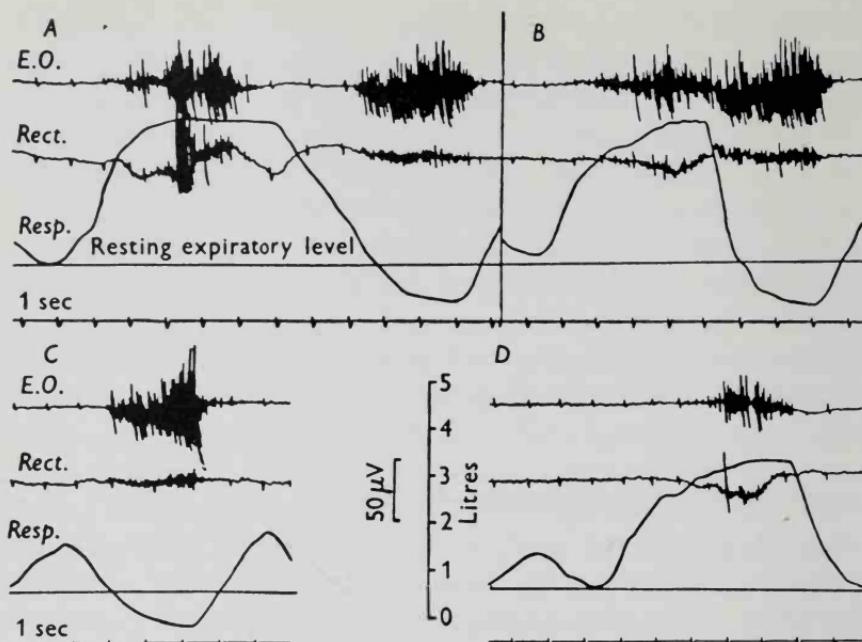
Fig. 126. EMG's of external oblique and rectus abdominis and spirometry of maximal inspiration and expiration. "Resp." is the spirometry trace (inspiration upward). *A*, inspiration held for 4 seconds and released, then followed by maximal inspiration; *B*, forced expiration within a second of attaining full inspiration; *C*, maximal expiration followed by normal inspiration; *D*, maximal inspiration followed by relaxation to the resting respiratory level. (Note: superimposed ECG spikes should be ignored.) (From Campbell, 1952.)

prominent at the beginning. He concluded that abdominal contraction was a factor in limiting voluntary inspiration, but in the presence of very rapid deep breathing due to asphyxia it was inhibited. It would seem, then, that contractions of the abdominal muscles to aid expiration only occurs in severe cases of greatly increased pulmonary ventilation under stress. In any case, they do not initiate the expiratory phase, but rather they help to complete it quickly. Campbell showed that a pulmonary ventilation of more than 40 litres per minute was required for the abdominal muscles to play their accessory respiratory rôle (fig. 127).
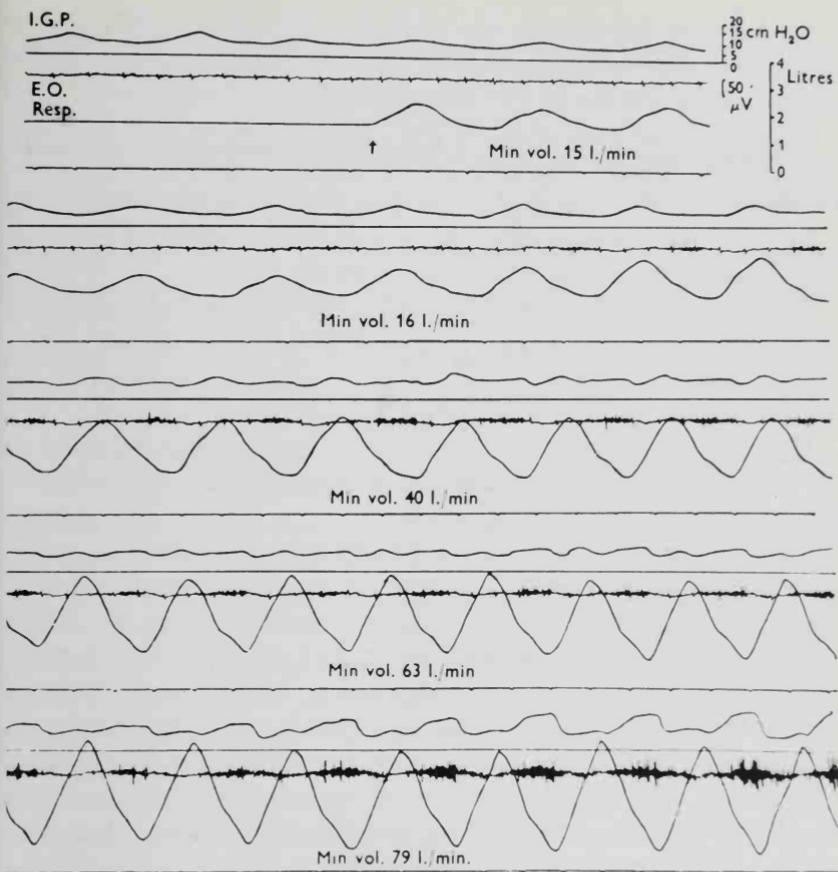
Fig. 127. Simultaneous EMG (E.O.), spirometry (Resp.) and recording of intra-abdominal (intragastric) pressure (I.G.P.) showing effects of progressively increasing pulmonary ventilation on the abdominal muscles. Continuous recording. (From Campbell and Green, 1955.)

Campbell and Green (1955) showed that the early findings were essentially true both in the supine and in the erect posture, but that normally in the erect posture there is some continuous activity in the muscles. This activity can be abolished by certain postures and is not particularly related to respiration.

In order to summarize the present knowledge of the rôle of abdominal muscles in respiration, it seems wise to present below the essence of the paper by Campbell (1955c):

The abdominal muscles are the most important and the only indisputable muscles of expiration in man. The obliques and transversus are much more important than the rectus abdominis.

Vigorous contraction occurs in all voluntary expiratory manoeuvres (such as coughing, straining, vomiting, etc.).

The abdominal muscles (almost exclusively the obliques) contract at the end of maximum inspiration to help limit its depth, but, in normal persons, they do not contract in hyperpneic asphyxia, apparently being inhibited by central mechanisms.

Hyperpnea with a ventilation rate of greater than 40 litres of air per minute calls upon activity of these muscles at the end— and only at the end—of expiration.

The finding by Fink (1960) of phasic expiratory activity in patients while being anesthetized does not (as Fink himself believes) invalidate Campbell's conclusion for normal subjects. Fink has, however, described a practical use of the integrated EMG of the abdominal wall muscles. He advocates it for monitoring the relaxation of the abdomen during operations in which the muscle-relaxant succinylcholine is used. I believe that the activity occurring during expiration under these circumstances is real and that the EMG provides an excellent tool for determining relaxation. Bishop (1964) has shown that continuous positive pressure breathing initiates expiratory activity of the abdominal muscles in cats.

Perineum

The muscles of the human perineal region that have been investigated are the external anal sphincter, the striated sphincter of the male urethra and the striated muscles of the pelvic floor and urethra in normal women and patients with "Manchester repairs" for prolapse. These studies will be considered in that order, following which, a brief account of reflex control of micturition will be given.
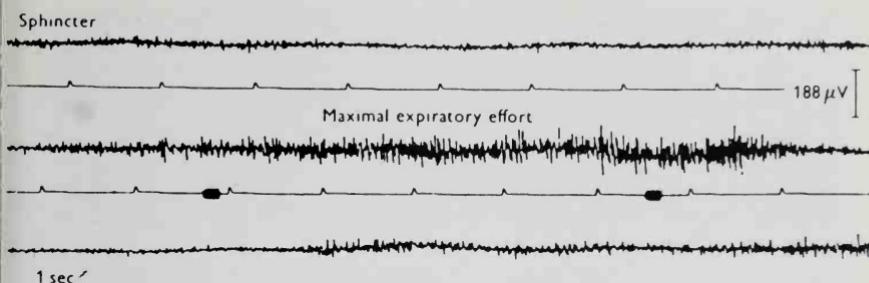
FIG. 128. EMG of external anal sphincter, showing resting tone and (between signal marks) the increase in tone during a maximal expiratory effort. The record is in three serial horizontal strips and reads continuously from left to right. (From Floyd and Walls, 1953.)

Sphincter Ani Externus

Aside from Beck's early electromyographic study (1930) of the anal sphincter almost exclusively in dogs, only Floyd and Walls (1953) have reported on the electromyography of this important muscle. Beck's results are now more provocative than useful; but those of Floyd and Walls are extremely interesting and practical. I have had occasion to confirm some of them coincidentally during a study of the urethral sphincter (see below).

Floyd and Walls found that the anal sphincter is in a state of tonic contraction (fig. 128). The degree of this tone varies with posture and the subject's alertness, falling to a very low level during sleep. Presumably, the internal sphincter is the main agency for keeping the rectum closed during sleep. They found that the subjects can voluntarily produce an outburst of activity in the anal sphincter. W. B. Spring and I (in an unpublished study) found that the contraction of sphincter ani externus is not isolated but is accompanied by general contraction of the perineal muscles, especially the sphincter urethrae. Since these muscles are of common origin from the cloacal musculature, these findings are not surprising.

With increased intra-abdominal pressure produced by straining, speaking, coughing, laughing or weight-lifting, Floyd and

Walls found increased sphincteric activity related in amount to the degree of pressure. This has been confirmed by Cardus *et al.* (1963) and Scott *et al.* (1964). However, actual efforts to defecate were usually (but not always) accompanied by relaxation of the sphincter ani.

Duthie and Watts (1965) found that electrical activity in the striated external sphincter, though greatly reduced, persisted even under general anesthesia. In response to rectal distension, the sphincter showed an increased activity as the maximal rate of diminution in pressure occurred. Thus relaxation in the anal canal is independent of the action of this sphincter which contributes to pressure only when a bolus is present.

Porter (1960) also has shown that the external sphincter and the pubo-rectalis show continuous activity at rest, heightened activity with effort and coughing, and inhibition with defecation and micturition. A critical volume brings about the desire for a bowel movement with sphincteric inhibition.

Striated Male Sphincter Urethrae

Our brief report (Basmajian and Spring, 1955) dealing with this almost inaccessible muscle, after years of virtual eclipse, has been referred to so often in recent years that it can be repeated here to advantage. Various authors have generously mentioned our early findings, which happily have been borne out by subsequent, more elaborate studies. We inserted very fine, self-retaining wire-electrodes through the perineum into, or very near, the sphincter urethrae in six men during cystoscopic examination. Action potentials of the muscles were obtained and recorded on our Stanley Cox 6-channel electromyograph.

We discovered that when the bladder is empty, there are a few, occasional, small potentials in the sphincter urethrae with long periods of inactivity. As the bladder is filled slowly through the cystoscope, the action potentials increase in number. There is a continuous low level of activity in the striated muscle surrounding the membranous urethra as long as the bladder contains fluid. When the subject is instructed to micturate after the cystoscope
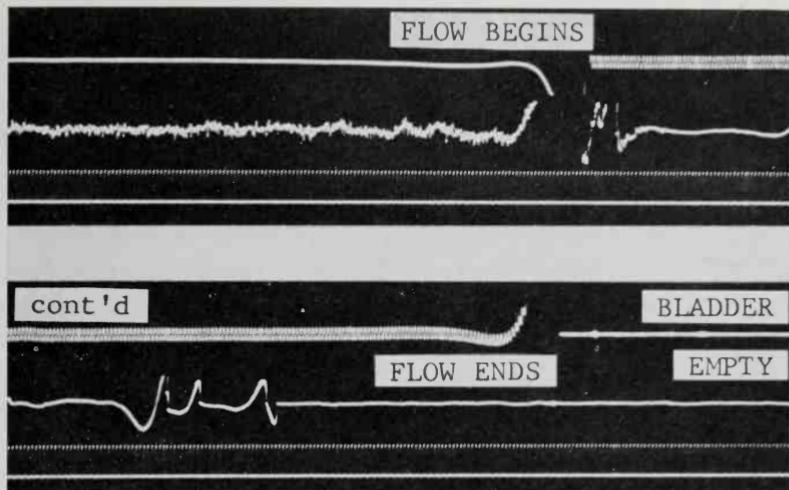
Fig. 129. EMG of male striated sphincter urethrae with partly filled bladder (continuous activity), during micturition (relaxation of sphincter) and with bladder empty (relaxation continues). Uppermost trace is a recording of urine flow ("flow begins—flow ends"); middle trace is EMG; and lowest trace is 10-msec time-marker.

is removed, the potentials disappear as micturition begins, and remain absent during the whole period of micturition and remain absent if the bladder is empty (fig. 129). Sudden voluntary stopping of micturition before the bladder is empty is accompanied by a marked outburst of potentials, the frequency of which then falls off rapidly to "the resting level."

Nesbit and Lapides (1959) in a study of male patients conclude that the striated sphincter is necessary for sudden interruption of micturition and for maintenance of continence when the vesical neck is incapacitated. Lapides is emphatic in his belief that micturition may be initiated and terminated consciously by voluntary effort without the use of any striated muscles and that urinary continence is normally maintained by the internal vesical sphincter, not by striated muscles. (See Lapides et al., 1957, 1960.) On the other hand, Susset, Rabinovitch and MacKinnon (1965) clearly show that under conditions of stress, such as coughing or
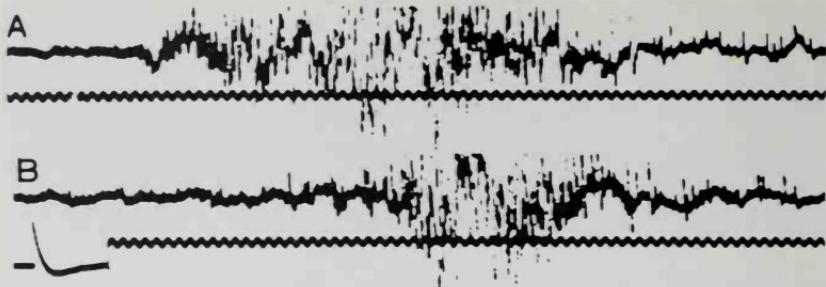
Fig. 130. EMG from bulbocavernosus, *A*, in voluntary contraction, and *B*, in coughing. Time in milliseconds. Calibration (*in lower left corner*), 100 μv. (From Petersén and Franksson, 1955.)

straining, the external sphincter is necessary and very active. A full bladder even results in minimal opening of the bladder neck on coughing, throwing added responsibility on the striated muscles. Susset *et al.* have also proved the importance of striated muscle spasticity in patients with upper motor neuron lesions; in such cases the external sphincter takes over the total function, and being spastic, obstructs micturition.

Meyer Emanuel's (1965) review of control of the bladder outlet appears to rationalize the findings of many types of investigation. In men, the urinary sphincter system consists of a tubular extension of the bladder containing elastic tissue with a collar of striated muscle at the urogenital diaphragm; in women this system accounts for the whole length of the urethra. Incontinence occurs only if both ends of the sphincteric system become damaged. The striated muscle is important for interrupting micturition, but it does not maintain sustained contraction indefinitely.

Petersén and Franksson of Stockholm (1955) reported the electromyography of the male striated urethral sphincter and the bulbocavernosus muscle in 10 and 11 patients, respectively. When their patients were asked to contract their muscles to stop micturition, there was a sudden burst of activity in the sphincter urethrae, just as in our findings, and similar activity in bulbocavernosus (fig. 130). This agrees, in general, with my opinion mentioned above, namely, that the cloaca-derived musculature contracts simultaneously and indiscriminately when one or the

other muscle is suddenly contracted. It also accounts for Muell-
ner's (1958) erroneous belief that levatores ani and the pubococ-
cygeus are the "primary muscles used to stop the urinary stream
voluntarily." Indeed, these muscles do also contract reflexly when
the sphincter urethrae contracts, but they have other functions
to perform.

Scott, Quesada and Cardus (1964) have found such a close
association in the activities of cloacal musculature that they use
electromyography of sphincter ani externus for the routine indica-
tion of activity in the striated urethral sphincter. Study of their
results reveals that they are indistinguishable from direct record-
ings from the urethral muscles.

To elaborate this point further, we studied the electromyog-
raphy and the morphology of the external anal sphincter and
external urethral sphincter in rabbits (Basmajian and J. R.
Asunción, 1964 unpublished; Basmajian, Sharon McKay and
Ron Hons, 1964, unpublished). The outstanding finding by both
techniques was the unseparable nature of the two sphincters.
The morphology is intricately linked; bundles of one sphincter
intermingle in a complex fashion with bundles of the other. In
rabbits (as in some other mammals) the structure is quite primi-
tively cloacal in nature when compared with that in man.

Franksson and Petersén (1955) have also reported emg studies
of patients with various disorders in micturition, convincingly
demonstrating neurogenic sphincteral disturbances in some. Such
studies must, of necessity, be expanded by urologists.

Giovine (1959) of Milan has also presented some electromyo-
graphic results from the striated sphincter. In addition, he re-
ported histological findings from which he concluded that the
muscle is made up of red fibres to a large extent. The significance
of red and white fibres not being firmly established, this matter
must await further study.

Pelvic Floor and Urethra in Women

The pelvic floor or pelvic diaphragm is mostly muscular, very
important in parturition, and generally misunderstood. Electro-
myography, one might suppose, would have been invaluable in

clearing up misunderstanding, but only one group has actually studied the musculature of the female pelvic floor—Petersén, Franksson and Danielsson (1955). This is the same Stockholm group mentioned before with the addition of a gynecologist, who then assumes senior authorship of a second paper on abnormalities of the pelvic floor (Danielsson, Franksson and Petersén, 1956).

In the first study, Petersén et al., using needle electrodes and without general anesthesia, explored: (1) the pubococcygeus which is the medial or most important part of the levator ani and (2) the urethral sphincter. The electrodes were inserted through the vaginal wall in 24 normal women (about half of whom had borne children). They concluded that some subjects were able to relax the sphincter urethrae completely, while others were unable to relax it. However, none could relax the pubococcygeal part of levator ani even though they were in the "lithotomy position."

Diminution or complete cessation of activity in the sphincter urethrae at micturition (or attempted micturition) agrees with our findings in men (fig. 131). Furthermore, their finding that voluntary efforts to contract the one muscle automatically recruits the contraction of the others agrees with my impression, already noted above, that individual contraction in the perineum is difficult if not impossible.

More recently, Petersén et al. (1962) proved in women that voluntary complete relaxation of the external sphincter was possible even with a partially filled bladder. Voluntary interruption of micturition results in a rapid closing of the striated external sphincter; only afterwards does the posterior urethra empty relatively slowly in a proximal direction. Considerable variations were found in normal persons.

Petersén et al. (1955) reported regional differences in the activity of the sphincter, and they stated that the pattern was more or less related to whether the subject had borne children. Nulliparous subjects showed little difference in the response of the whole circumference of the sphincter while the multiparous subjects had much less or even no activity in the dorsal part of the sphincter. This dorsal part, related as closely as it is to the vagina, might
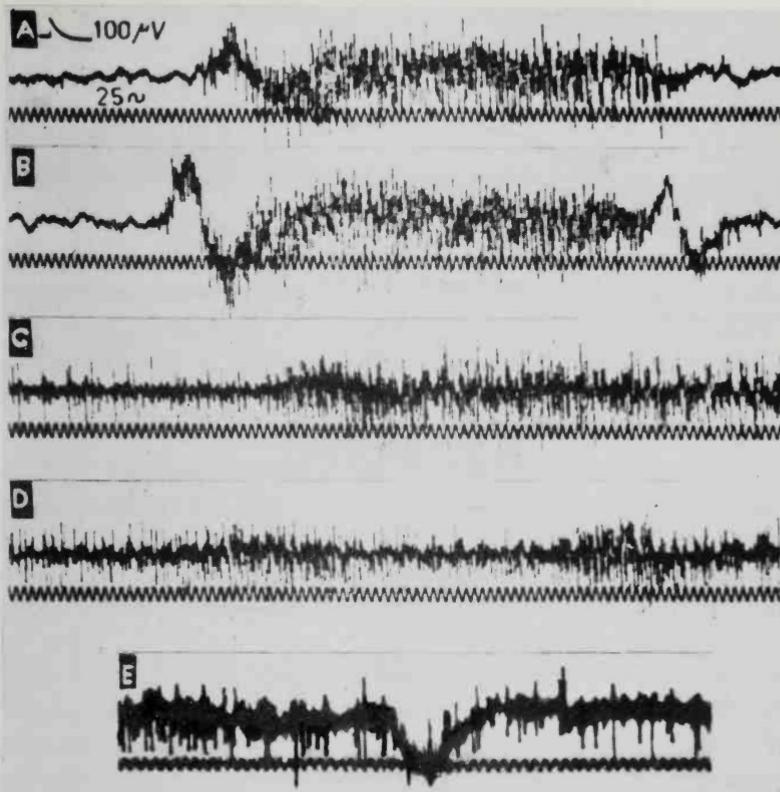
FIG. 131. EMG's from normal female sphincter urethrae during A, voluntary contraction, and B, a cough; and from pubococcygeus during C, voluntary contraction, D, a cough, and E, an attempt to micturate. (From Petersén et al., 1955.)

have been destroyed by laceration in the course of childbirth, according to these investigators. Pubococcygeus, however, showed no difference attributable to parity.

Danielsson et al. performed electromyographic explorations with similar techniques on women who had recovered from the Manchester reparative operation for prolapse but who were still complaining of urinary stress incontinence. In all of these women there were no electromyographic potentials obtainable from the
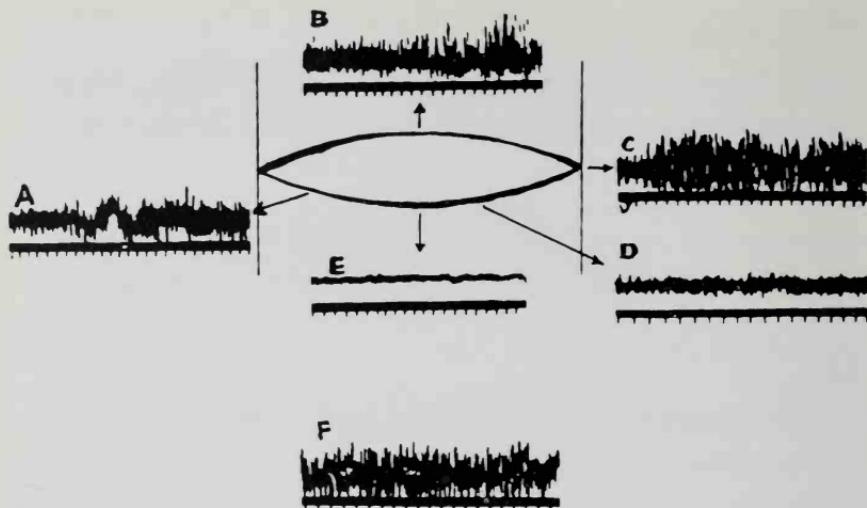
FIG. 132. EMG of abnormal sphincter urethrae of woman who had borne three children and had had a Manchester operation. B, ventral part of sphincter; E, dorsal part (nearest vagina); A, C and D, from sides; F, from normal pubococcygeus. (From Danielsson et al., 1956.)

dorsal part of the urethra, suggesting again that the part of the sphincter urethrae next to the vagina had been torn by parturition (fig. 132). Lesions of the pudendal nerves, either at childbirth or at the time of the Manchester operation, may have also played a rôle.

Spinal Reflex Activity from the Bladder

Bors and Blinn (1957) of Long Beach, California, have presented convincing evidence that demonstrates the importance of the bladder mucosa in influencing the striated musculature of the pelvic floor. Thus, the sphincter ani and the sphincter urethrae contract in response to mucosal stimuli of the bladder wall. Our own finding that filling of the bladder with more than a few cubic centimetres of water starts up activity in the male sphincter urethrae is in agreement with this. The further findings of Bors and Blinn (1957, 1959) and of Pierce et al. (1960), demonstrate that all these reflexes may be grouped simply under one generic

term, "the bulbocavernosus reflex;" this reflex may be elicited from the stimulation of any genitourinary mucosal surface including the glans penis. (But see the contrary and less convincing view of Rattner *et al.*, 1958.)

Relationship of Abdominal and Perineal Muscles

Bors and Blinn (1965) investigated the activity of the rectus abdominis in relation to micturition and to contractions of perineal muscles. Before or at the onset of micturition, whether *on desire* or *on volition*, the EMG of rectus abdominis usually remained unchanged; also at the normal cessation of micturition there was generally little or no reaction in most subjects. However, when either micturition was suddenly interrupted or the external anal sphincter was consciously contracted, activity in rectus abdominis usually increased. There would seem to be a related contraction of abdominal and perineal muscles, but the exact relationship is still obscure. Bors and Blinn's view is "that phasic contractions of the pelvic floor cast their shadow upon the abdominal muscles."

EMG of Ejaculation and of Penile Muscles

In a preliminary study, Kollberg, Petersén and Stener (1962) reported the train of events recorded electromyographically from the striated external sphincter urethrae and adjacent striated muscles. Some seconds before ejaculation occurs there is a lively contraction in muscles of the u.g. diaphragm. The cause or effect of this remains obscure. It may play some role in penile engorgement just before ejaculation. On ejaculation, the sphincter (and probably its neighbours) contract rhythmically for 15 to 20 times in about 25 seconds. These contractions, which must have some part in propelling the semen, appear as salvoes of action potentials alternating with quiet intervals. Some reciprocity is also noted, i.e., activity in the muscles alternate. Perhaps, these enterprising Swedish investigators will also succeed in recording the state of contraction of the smooth muscle at the neck of the bladder which is so often believed to prevent reflux of sperm into the bladder.

Hart and Kitchell (1966), using special bipolar needles, recorded

the emg activity from the penile muscles of dogs—ischio-ure-thralis, bulbocavernosus and ischiocavernosus. Different patterns of reflex activity were obtained on light stimulation of different parts of the penis. Rubbing behind the bulbus glandis elicited tonic contractions of the ischio-urethralis, rhythmic contractions of the other two muscles and rapid penile detumescence. This reflex would seem to be related to normal responses in ejaculation. Penile tumescence was then obtained by application of pressure behind the bulbus glandis and rubbing the urethral process; the tumescence was accompanied by the same pattern of activity in the three muscles. Stimulation of the corona glandis resulted in tonic contraction of the bulbo- and ischiocavernosus muscles, again accompanied by rapid detumescence; but this reflex is not as amenable to explanation.

CHAPTER *15*

Muscles of Respiration

The muscles usually considered to be the primary muscles of respiration are the diaphragm and the intercostals, but the following also have been implicated as either primary or accessory in respiratory function: the scalenes and the sternomastoid in the neck, the musculature of the shoulder region including the pectoral muscles and serratus anterior, and the anterior abdominal muscles. These "accessory" muscles are discussed, but only briefly, at the end of this chapter, and reference is also made in appropriate places elsewhere to the broader aspects of each group of muscles.

Since the earliest recorded medical history, respiration and its mechanical production have been the subject of inquiry. Both before and after Galen, theories waxed and waned. Galen in the second century was perhaps the first to direct attention to the action of the intercostals though he did not belittle the rôle of the diaphragm in breathing. Furthermore, he was aware of the two layers of intercostals—external and internal. His assignment of inspiration to the former and expiration to the latter still reaches down to the present day, causing renewed controversy. Such

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illustrious names as Willis, Hamburger and Magendie continue to appear in any history of the respiratory function, but a review of their work here would serve no particular use.

Toward the end of the nineteenth century, Martin and Hartwell (1879), from crude experiments in anesthetized cats and dogs, made conclusions that were not much different than those of Galen. The history of our knowledge of diaphragmatic function unfolded until the turn of the century. Newer techniques and medical advancement have increased our knowledge of the function of the muscles of respiration, but have not lessened the arguments.

In the past decade, electromyography has provided a tool which promises to remove much of the uncertainty. Already there has been definite progress which will be reported in some detail in this chapter. The names of Jones, Pauly, and Beargie, then of Chicago; Campbell of London; and Koepke, Smith, Murphy, Rae and Dickinson of Ann Arbor, Michigan, all stand out prominently in any review of this subject. Contributions have also been made by others; these will be mentioned in the appropriate places. Studies on the diaphragm have been particularly voluminous in the past four years since the first edition of this book.

It is convenient first to consider the movements of the ribs and the muscles that produce these movements.

Costal Respiration

Jones, Beargie and Pauly (1953) were the first to make a substantial electromyographic contribution to the knowledge of costal respiration. With surface electrodes over the upper four internal and external intercostals, the scalene muscles in the neck, and the abdominal muscles, they put their subjects through various tests.

The usual concept of normal quiet breathing is that the scalenes anchor or fix the first rib while the external intercostals elevate the remaining ribs towards the first—this in spite of radiographs showing no approximation of the ribs. Jones and his colleagues showed that both sets of intercostals in man were slightly active

constantly during quiet breathing and showed no *rhythmic* increase and decrease. In contrast with this, the scalenes did show a rhythmic increase during inspiration (fig. 133). Their rôle in quiet breathing was confirmed with needle electrodes by Raper *et al.* (1966).

With forced inspiration, the scalenes, sternomastoid, and internal and external intercostals showed marked activity (Jones *et al.*, 1953; Raper *et al.*, 1966). In contrast, with forced expiration, the scalenes were quiescent while the intercostals were still active. Attention was focussed anew on the scalenes as fundamental muscles of inspiration.

These findings led Jones, Beargie and Pauly to the conclusion that the function of the intercostal muscles in respiration is to supply the tension necessary "to keep the ribs at a constant distance from each other while the chest is expanded from above and contracted from below." They insisted that passive membranes between the ribs instead of muscles would be inadequate because they would be sucked in and blown out during respiration. Therefore, they would not provide the constant fine control of the rib positions. Moreover, the intercostals were shown to function in flexion of the trunk (as in sitting up from the supine position) and, probably for the first time, they were suggested as being postural muscles.

This group of investigators emphasized the belief that the main rôle in human respiration is performed by the diaphragm, while the intercostals were necessary for markedly increasing the intrathoracic pressure. Thus they were agreeing with Hoover (1922) who showed that a person with paralyzed intercostals had a sharp reduction of sucking and blowing power with comparatively much less embarrassment of quiet respiration. In a later paper, Jones and Pauly (1957) state that perhaps the intercostal muscles are "used in nonrespiratory activity more than in ordinary respiration." (See also Pauly, 1957.)

Campbell (1955a) did not agree completely with these American workers. Using interspaces (6th, 7th and 8th) lower than those that they had used for recording, he concluded that in quiet
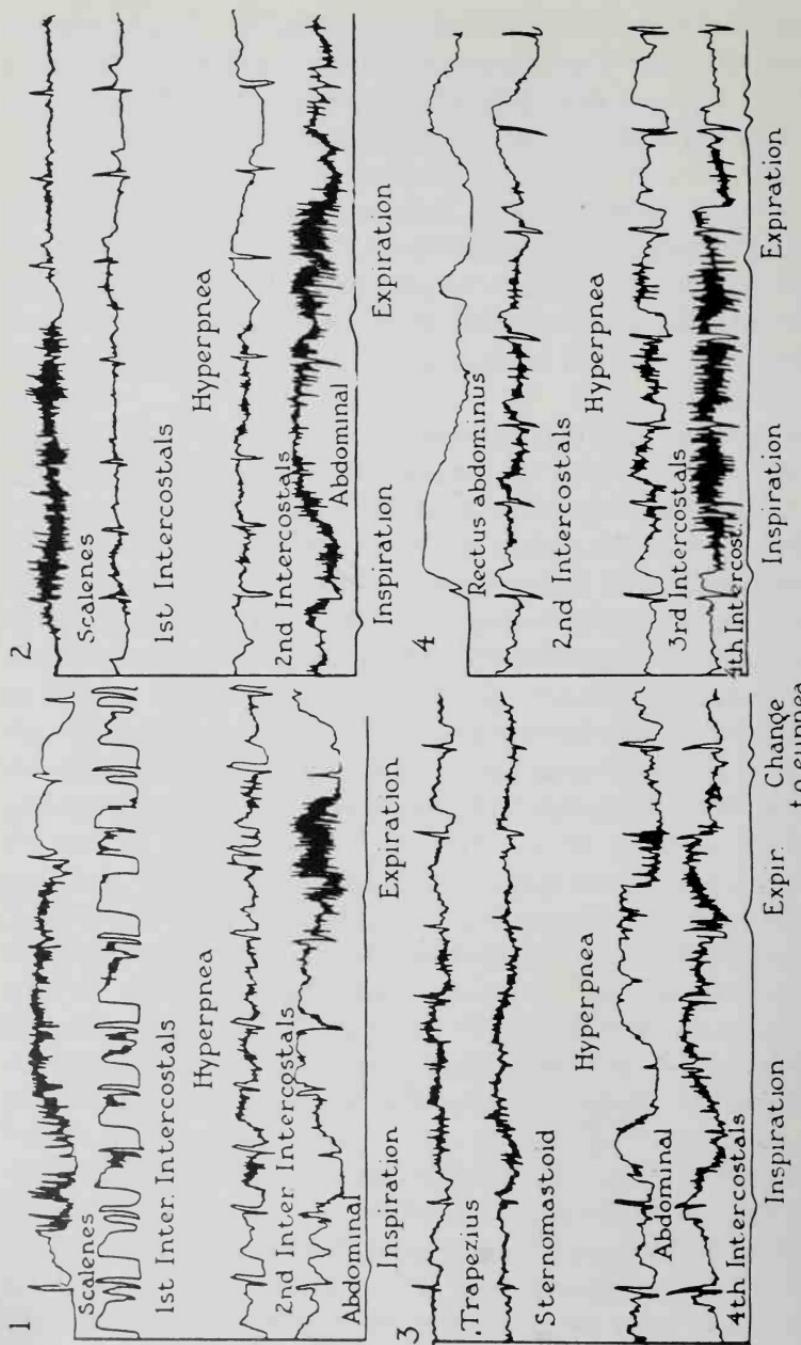
FIG. 133. Four EMG's of scalenes and intercostals and other muscles during four different respiratory cycles. (From Jones, Beargie and Pauly, 1953.)
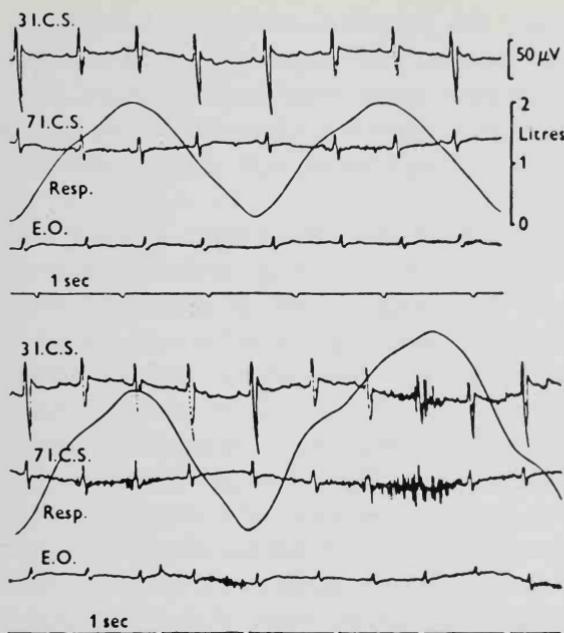
Fig. 134. EMG's of intercostal muscles (3rd and 7th intercostal spaces—3 I.C.S. and 7 I.C.S.) and of external oblique of the abdomen (E.O.) along with spirometry (Resp.). (From Campbell, 1955a.)

breathing the intercostals contract during inspiration and completely relax during expiration. He went further in his disagreement by stating that considerable hyperpnea (forced breathing) still did not recruit intercostals in expiration (fig. 134) (see also Campbell's 1958 monograph, *Respiratory Muscles*, for further details).

From the work that we have done, it appears that the findings of both groups may well be correct—the apparent disagreement arising from the use of different interspaces for the two studies. Koepke *et al.* (1958) showed electrical activity in the 1st, 2nd and 3rd interspaces in quiet breathing but none in the 4th, 5th and 7th. These inherent differences that have been revealed have not yet been explained, but in their rationalization may lie the final solution of the rôle of the intercostals in breathing. In spite of

this indecision, the following cannot be ignored: (1) the vital rôle of the scalenes as ordinary respiratory muscles, (2) the possible rôle of the intercostals as primarily postural muscles, (3) the marked differences in activity which are found between different interspaces and (4) the primary rôle of the diaphragm in respiration.

In deeper breathing, Koepke, Smith, Murphy and Dickinson (1958) showed that the lower intercostals that were so noticeably silent in quiet breathing became progressively recruited in descending order until even the lowest became active on very deep inspiration. This pattern of recruitment is further discussed below (p. 303). Hirschberg's (1957) studies on patients with partial respiratory paralysis tended to confirm the findings for normal patients. Generally the intercostals are recruited during inspiration but not during expiration. Morosova and Shik (1957) of Moscow, from an electromyographic study of respiratory muscles, have concluded that in patients with various respiratory deficiencies extreme augmentation of the electrical activity occurs. This suggests that there is some form of compensatory stimulation *via* the respiratory centre of the central nervous system.

Draper *et al.* (1957) and then Taylor (1960) re-awakened the Galenic teaching that the external and internal intercostals had different functions. Although many other workers could find no evidence for this with standard needle electrodes, Taylor succeeded in a long series of human subjects by probing with very fine needle electrodes. He demonstrated that there are two functionally distinct layers of intercostal muscle everywhere except anteriorly in the interchondral region and posteriorly in the areas medial to the costal angles.

Where there are two functional layers, the superficial one (external intercostal) acts only during inspiration and the deeper (internal intercostal) during expiration. Thus, Taylor seems to have proved in man what has been common experience in experimental animals for centuries.

Taylor found that in quiet breathing what emg activity that occurs is limited to the parasternal region during inspiration—

here there is only one functional layer and it is exclusively internal intercostal. This explains why other workers, who usually study internal intercostal in this very place because here it is not covered by the external intercostal, have generally considered internal intercostal to be inspiratory. Indeed, this part of it *is* inspiratory, according to Taylor. Yet, to confuse the issue, Nieporent (1956) found this same part to be active in expiration. (See also the discussion of the work of Hirschberg *et al.* on p. 307.)

During expiration, in quiet breathing, Taylor found emg activity limited to the lower lateral part of the thoracic cage and coming from the internal intercostals. Apparently he found no external intercostal activity whatsoever in quiet breathing.

His finding of intercostal expiratory activity even in quiet breathing disproves the old theory that expiration is entirely passive. Probing deeper, Taylor found that the transversus thoracis is purely expiratory in function—including its parts known as sternocostalis, intercostales intimi and subcostalis.

More vigorous respiratory effort brings the layers of muscular activity into reciprocal action all over the chest wall. Now the external layer is entirely inspiratory and the internal layer expiratory. Taylor suggests that these two layers exert opposite rotational forces on individual ribs around their long axes. At this point, obscurity creeps into the interpretation that one might put on the rôle of such possible rotation; no purpose is served in speculating further here.

EMG of Intercostals during Phonation

Since the early and unsubstantiated work of Stetson (1933) no great progress was made in this type of study until the '60's. Hoshiko (1960, 1962) has investigated the sequence of activity during phonation from the intercostals and rectus abdominis. Whatever the speech material and rates of utterance may be, the internal intercostals are always recruited first, followed by the rectus abdominis and then the external intercostals. Action potentials disappear at the end of phonation in the external intercostals.

Hoshiko believes that the internal and external intercostals

cooperate in releasing a syllable, i.e., initiating the simple pulse associated with syllabication. Contrary to Stetson's teaching, the external intercostals are not involved in terminating the syllable movement.

Diaphragm

As indicated above, the main respiratory muscle, at least in man, is the diaphragm. Most emg studies of this vital muscle—except the most recent ones—have been indirect. Admittedly, studies of the diaphragm in experimental animals under anesthesia are not rare, but, being conducted under highly unphysiological conditions, they can hardly give definitive answers to a vital problem. For example, a recent emg study by Di Benedetto *et al.* (1959), which appears to be as technically acceptable as most such studies, used dogs that were actually hepatectomized in addition to their bellies being left wide open during the tests. To be fair to these workers, we must note that they were not attempting to categorize the actions of the diaphragm in detail. However, many of the statements on diaphragmatic function in the textbooks are based on exactly this type of observation, with or without electromyography.

The function of the diaphragm has been of longstanding interest. Recognition of its importance dates back to Hippocrates, but he attributed no movement to the diaphragm. During the past 100 years, various comprehensive studies (see Boyd and Basmajian, 1963) showed that the diaphragm—at least when stimulated electrically—expands the base of the thorax by moving the ribs upward and outward. Other studies combining fluoroscopy and spirometry showed that a change from the erect to the supine position causes marked alteration in the pattern of diaphragmatic movement in man.

J. C. Briscoe (1920) and G. Briscoe (1920) postulated that the diaphragm is a tripartite organ consisting of the right and left costal parts and the crura forming one part. This view was supported by the fact that the costal and the crural parts develop from different muscular sheets.

Research on anesthetized rabbits by Wachholder and McKinley (1929) showed that the diaphragm was almost continuously active during quiet breathing with only brief relaxation during expiration. Campbell's (1958) attempts to confirm these findings in normal human subjects with surface electrodes met with disappointing results because of the intervening mass of bone, cartilage and lung. Studies of diaphragmatic activity in many species, ascribed to Chennells by Campbell (1958), apparently showed that there is no activity during expiration. In human subjects Nieporent (1956) and Draper et al. (1957) found that diaphragmatic activity could be obtained with needle electrodes during inspiration, but there was none during expiration. However, other workers, also using needle electrodes, showed that diaphragmatic activity in man could be recorded during both inspiration and expiration (Koepke et al., 1958; Murphy et al., 1959; Petit et al., 1960).

In recent years, then, little if any advance has been made in our understanding of the total function of the diaphragm. This fact led to our detailed investigation in which recordings were made simultaneously from indwelling multiple electrodes (up to 16) along with spirometric tracings in conscious rabbits. The correlated results provided the first complete account of the activity of the whole diaphragm in quiet breathing (Boyd and Basmajian, 1963).

A series of 25 adult male rabbits had multiple clip electrodes implanted in their diaphragms at open operation. Following postoperative recovery, the wires from these electrodes were connected to an electromyograph and records were made along with spirometry under normal physiological conditions. A colour motion picture demonstrates our techniques (Basmajian and Boyd, 1960).

The rabbit's diaphragm, like man's, is divided clearly into eight left and eight right muscular slips or digits. Each side of the diaphragm has one sternal slip, six costal slips and a lumbar slip from the aponeurotic arches and crus. The muscular slips may be numbered anteroposteriorly: sternal slip—1; costal slips—2 to 7; and lumbar slip, including fibers from the crus—8.

The question as to whether the diaphragm is functionally a single muscle, or two functional halves, or a tripartite organ with a lumbar or crural portion and two costal portions was answered conclusively: all portions of the diaphragm contract simultaneously. Almost certainly, the whole diaphragm normally functions as a unit. This is true also in the cat, as shown by Sant'Ambrogio *et al.* (1963). Most likely it is true in all mammals.

Phases of Respiration

One of our main findings was that quiet respiration includes not only the two simple opposite phases of inspiration and expiration but also a static phase before each. These we have called pre-inspiration and pre-expiration. In duration, they are much shorter than the air-moving phases; nonetheless, the static phases make up an appreciable part of the respiratory cycle. They would appear to correspond to the well-known inspiratory and expiratory "pauses" in man.

Pre-inspiration

This static phase, which occurs prior to inspiratory air movement, lasts from 20 to 120 msec. During pre-inspiration, the activity is rarely greater than 1 +, or slight.

Other workers noted activity occurring in the diaphragm before the onset of active inspiration without recognizing a static phase. With needle electrodes, Koepke *et al.* (1958) determined from spirometric tracings that the onset of contraction in human subjects occurred as much as one-fourth of a second before the onset of inspiration. This finding was confirmed by Taylor (1960), whose studies showed that action potentials began immediately before inspiratory airflow, increased rapidly to a maximum, and died away in the first half of the expiratory phase. Similar findings were reported by Petit *et al.* (1960) using esophageal electrodes in man.

Inspiration

Inspiration is an increase in the volume of the thorax with an actual inward flow of air. The diaphragm contracts and increases

the cavity in a caudad direction and perhaps in the ventrodorsal and lateral directions as well. The motor units of the diaphragm increase their rate of firing at the onset of inspiration and as this phase proceeds, new units are added or "recruited" so that the inspiratory effect gains force as it proceeds (Bergström and Kerttula, 1961; Lourenço et al., 1966). As inspiration continues, the individual motor units in the diaphragm accelerate in rate, resulting in a progressive increment in the strength of contraction of each unit. With an increase in the number of active units and by augmentation in the strength or frequency of each unit, inspiration reaches its peak. In all but an insignificant number of our records, activity was recorded throughout the entire inspiratory phase. Indeed, activity was continuous throughout both pre-inspiration and inspiration. However, the level of activity fluctuates over these phases.

The entire inspiratory phase in rabbits lasts from 300 to 550 msec (and rarely longer). This inspiratory phase may be divided for convenience into four quarters. Of course, the length of these varies with the length of each phase, which in turn depends on the respiratory rate.

The peak of the inspiratory motor unit activity terminates some 30 to 40 msec before the end of inspiration. In most instances, the peak is followed by a rapid decline—and in some instances by a very sharp drop—to the base line, where varying degrees of activity continue to the end of the fourth quarter of the inspiratory phase. A similar finding was reported by Koepke et al., indicating that the diaphragmatic voltage pattern in man consistently reached its greatest amplitude at or slightly before the end of inspiration; then it tapered to its stopping point in what was considered to be expiration. No instance was found during which activity stopped at the end of inspiration in man; but we found electromyographic silence following inspiration in 44% of the recordings in rabbits.

At the onset of inspiration, almost all of our recordings (98%) showed a carry-over of pre-inspiratory activity into the first quarter of inspiration. Then, in all of the recordings, activity was present throughout the second and third quarters of inspiration.

During the first quarter of inspiration, in general, the diaphragm is only slightly active. The motor units of the diaphragm do not begin to increase their rate of firing during quiet breathing until the second quarter of the inspiratory phase is reached; most of the recordings (74%) show moderate activity by that time. One might postulate that the intercostals play the main role in the first quarter.

The third quarter of inspiration forms the peak for inspiratory activity during quiet normal respiration with 76% of our recordings showing marked activity. Nonetheless, in a substantial number (12%) the activity remains only slight during the third quarter.

The activity in the third quarter of inspiration, whatever its character, is carried into the fourth quarter. In 76% of the recordings the great activity recorded during the third quarter continued into the fourth quarter and stopped some 20 to 40 msec before the termination of the inspiration. However, the great activity at the peak of the inspiration does not continue throughout the entire fourth quarter. The fourth quarter thus can be divided into two unequal parts, the line of demarcation being the terminal point at which the muscular activity ceases. Thus, during the first part of the last quarter, 76% were markedly active and the remainder moderately or slightly active (12% each).

Great activity when it did occur at the end of inspiration (7%) was never carried into pre-expiration in our series.

Pre-expiration

The static phase of pre-expiration usually lasts from 20 to 50 msec (and somewhat longer in some cases). Electromyographic activity is slight or absent (44% and 56%, respectively) in this phase.

Pre-expiration is a regular precursor of expiration. Studies on the human diaphragm by Murphy *et al.* during passive expiration seemed to show that electrical activity always continued from inspiration into expiration. They reported that the carry-over occurred in all subjects, and that this activity occurred even though

each subject had been instructed to relax after taking in a breath. They found that an increase in the duration of activity during expiration was directly related to the depth of the preceding inspiration. These findings could not be confirmed in our study, for most of the recordings were taken during quiet respiration and, of course, they were in non-human subjects.

Expiration

Expiration, the last phase in the respiratory cycle, consists of a decrease in the volume of the thorax with air moving outward. One way that this might be accomplished actively is by the contraction of the abdominal muscles forcing the diaphragm up into the thorax. During quiet breathing, however, expiration is generally regarded as passive. Nonetheless, activity in the diaphragm is recorded during expiration. In almost every instance, the (slight) activity that we recorded during expiration lasted for a longer period of time than did the greater activity that occurred in inspiration. Previous to our findings, Murphy *et al.* reported that the activity continued through as much as 98% of expiration; Agostoni *et al.* (1960) found activity persisting into the early part of expiration in human diaphragms.

Many varied opinions exist on the activity of the diaphragm during expiration. The literature includes only one study specifically in the rabbit (Wachholder and McKinley, 1929). This report indicates that the diaphragm is almost continuously active during quiet breathing with only a very brief period of non-activity during expiration. In contrast, using needle electrodes, Nieporent (1956), Campbell (1958), and Draper *et al.* (1957) found no diaphragmatic discharge during the expiratory phase in man or in animals.

Murphy *et al.* (1959) found no activity originating in the human diaphragm during forced expiration; they reported that activity occasionally carried over from deep inspiration but always stopped abruptly at the onset of a forced expiratory effort. In patients with transverse myelitis, irrespective of the size of the preceding inspiration, diaphragmatic voltages were not found during a

forced expiratory effort. During passive expiration, activity always continued from inspiration into expiration, and this pattern was like that in normal subjects.

During quiet breathing in man (Petit *et al.*, 1960) activity started in the diaphragm at the beginning of inspiratory flow, increased in intensity through inspiration, and persisted after the onset of expiration, but with decreasing intensity. A similar pattern occurred during increased ventilation, with the difference that the activity started before the beginning of inspiration. Some workers tend to agree that there is a carry-over of inspiratory activity into the expiratory phase, but none indicates either how far into the expiratory phase this activity extends or the degree of activity carried into expiration.

In most of our recordings (63%), some activity occurred throughout the entire expiratory phase. Complete absence occurred in only 14%. Almost always the diaphragm is active during the last quarter of expiration. One possible reason why activity carries into or continues throughout expiration is that activity in the diaphragm during passive expiration is a braking action to oppose the normal elastic recoil of the lungs (Murphy *et al.*, 1959). In effect, it is not a true expiratory effort. Agostoni and Torri (1962) hold like views from like findings in man. However, they implicate reflexes to balance the antagonist activity of the abdominal wall muscles. Delhez *et al.* (1963 *et seq.*) discount the importance and even question the occurrence of activity at the end of forced expiration.

The anatomical structure of the diaphragm supports this view because all of its fibres are arranged in radiating fasciculi inserting into the central tendon. Shortening of the fibres can only cause a flattening of the dome and so actually resist the production of an expiratory force. Furthermore, no electrical activity could be recorded during forced expiration in human subjects.

According to Campbell, the rate of airflow at the onset of expiration does not rise rapidly to a maximum (as would be expected if the muscles of inspiration relaxed immediately), indicating that during the early part of expiration the muscles of inspiration

decrease their force of contraction only gradually. He further states that there is a persistence of intercostal activity during the early part of expiration. Although no direct reference to the diaphragm is made, he reports that measurements of the work of breathing based on pressure-volume diagrams suggest that the muscles of inspiration may exert considerable force in opposing the elastic recoil of the lungs during expiration. One may conclude, then, that the slight activity recorded from the diaphragm during expiration is a braking action to oppose the normal elastic recoil of the lungs.

Koepke *et al.* (1958) at Ann Arbor, Michigan, have also been making a concerted attack on problems of the respiratory muscles including the diaphragm. They have used needle electrodes in the diaphragm in several human subjects. These electrodes were inserted through the 11th intercostal space into the muscular digit of the diaphragm that arises from the 12th rib. We must keep in mind the limitations imposed by this localization of pickup (in a muscle which—in our own findings on rabbits—may act somewhat differently in its various parts). With ordinary inspiration, the diaphragm became active before any of the intercostals and before the flow of air by as much as a quarter of a second. During quiet breathing the diaphragm never failed to act in inspiration although some of the intercostals were only recruited with deeper breathing (see above).

The same group, with Murphy as senior author (1959), reported on the emg activity during expiration. They insisted that the diaphragm always shows electrical activity as a carry-over into the early stage of passive expiration (fig. 135). The diaphragm consistently showed its greatest activity at or slightly before the end of inspiration; this tapered off to silence in early expiration. The duration of activity in the diaphragm during expiration was directly related to the depth of the previous inspiration. In some instances, the activity continued through as much as 98% of expiration. None of the intercostal muscles showed the same degree of carry-over of activity as did the diaphragm. During quiet breathing *only* the diaphragm showed such expiratory activity.
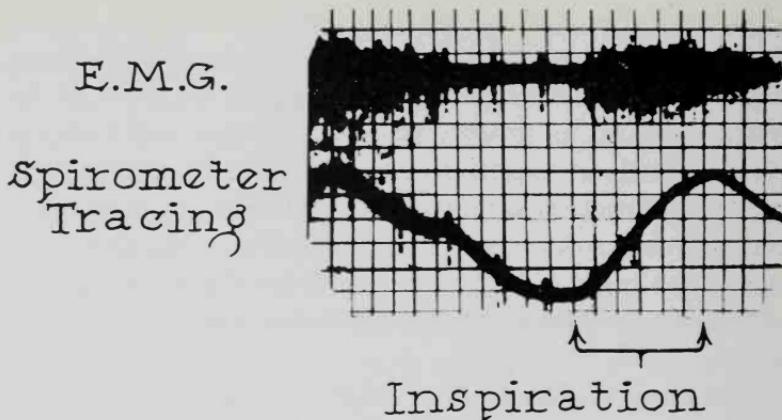
FIG. 135. EMG of diaphragm. (From Murphy *et al.*, 1959.)

Murphy *et al.* suggest that the activity of the diaphragm during passive expiration may be a braking action "to oppose the normal elastic forces of the lungs rather than the exertion of a true expiratory effort." Observing that the fibres of the diaphragm radiate from the central tendon, they too believe that activity of the muscle can only flatten and lower the dome. Furthermore, no activity in the diaphragm was seen during forced expiration, which appears to confirm their thesis.

Quite recently, a group of investigators in Belgium (Petit, Milic-Emili and Delhez, 1960) devised a novel technique for diaphragmatic electromyography in conscious man. The electrical activity was detected by means of electrodes passed down the esophagus to the level of the diaphragmatic esophageal hiatus. In four normal persons they found the activity to be synchronous with the respiratory variations of intra-abdominal and intra-thoracic pressures. Potentials occurred from the onset of inspiration and increased in intensity. They continued into expiration for a varying length of time with decreasing intensity. During increased ventilation, potentials began immediately before inspiration rather than just at its onset.

Admittedly, the intra-esophageal electrodes pick up potentials only from the crural fibres of the diaphragm, but this does not invalidate the results. Though in the future we may show some

variations between various parts of the diaphragm, no major differences are likely to be revealed. In any case, the new approach of Petit's group to diaphragmatic electromyography is a promising one.

Breath-holding

Agostoni (1963) has reported a curious diaphragmatic activity during human breath-holding. After an initial silence, a marked discharge occurs and repeats at progressively higher rates until the breaking point. These are ineffectual respiratory efforts that cause a fall of intrathoracic pressure apparently because the glottis is clamped shut by effort. Agostoni *et al.* (1960) found a rather similar fluctuation during the very brief episode of either coughing or laughing.

Quadratus Lumborum as an Accessory

In a later study using our earlier techniques, Boyd, Blincoe and Hayner (1965) showed that quadratus lumborum acted simultaneously with the diaphragm to stabilize the rib which might otherwise be elevated. Thus quadratus acts in concert with the diaphragm as a respiratory muscle; further, its activity coincides with the diaphragm to produce the normal braking action during expiration noted on p. 302.

Diaphragm-Intercostal Interrelationship

Although many generalized statements have been made in the literature (both of respiration and of electromyography) about the interplay of diaphragmatic and intercostal activity, only the work of the above-mentioned Ann Arbor group (Koepke *et al.*, 1958; Murphy *et al.*, 1959) and our own studies appear to cast any direct light on their relationship. As noted already, during quiet respiration, the diaphragm became active as much as a quarter of a second before the onset of inspiratory air flow as measured by spirometry. Furthermore, this occurred before any activity in any intercostal muscle. The intercostals that were recruited earliest were the first topographical pair (i.e., the first intercostal

muscles). Then, the recruitment proceeded progressively to in-
clude lower and lower intercostals. With quiet breathing the di-
aphragm was always active in inspiration, the 1st intercostals
usually were, and the 2nd intercostals occasionally were. All the
others were inactive. During inspirations deep enough to call upon
all the intercostals, the onset of activity advanced progressively
in successively lower intercostals.

During natural passive expiration (as distinct from forced ex-
piration) these workers found that a carry-over of activity was also
present in the intercostals. Among them, the lowest intercostals
were more important than the highest, the duration decreasing
sequentially from the 11th pair upwards.

Though no activity was found in the diaphragm during forced
expiration, intercostal activity was almost always present. The
likelihood of such activity was related inversely to the volume of
air in the lungs at the end of inspiration. When intercostal activity
was present during forced expiration the recruitment again was
progressively upwards from the lowest intercostals to the highest.

Murphy and his colleagues postulated that when the intercos-
tals are recruited sequentially from below upwards during forced
expiration the lower portion of the thorax becomes relatively
smaller than the upper to produce a desirable pressure gradient
within the chest to empty the lungs. This remains pure hypothesis
and is not, as yet, particularly convincing.

Other Respiratory EMG Studies

Fink *et al.* (1960) used the integrated emg recording of patients
during general anesthesia to study the threshold of the respiratory
centre. Though their study revealed nothing about the normal
functioning of the diaphragm, it did show the feasibility of human
diaphragmatic EMG's. They inserted unipolar needle electrodes
into the diaphragm through the 8th, 9th or 10th intercostal space
and successfully obtained recordings. Their main findings relating
to the onset of apnea revealed—as indicated by cessation of di-
aphragmatic potentials—that it occurs when the average alveolar
carbon dioxide tension or pressure falls to 38 mm Hg. Diaphrag-

matic activity reappears as the CO_2 tension rises above this value, the stimulus acting through the CO_2-sensitive respiratory centre.

The studies of Björk and Wåhlin (1960) on the effects of the muscle-relaxant drug succinylcholine upon the cat diaphragm would be of interest to a very few readers and are mentioned here for completeness only. The effect of the drug is to disturb the synchronization of parts of the motor unit and to cause a progressive decay of motor unit potentials down to individual fibre potentials. This effect is peripheral rather than central.

Di Benedetto et al. (1959) used electromyography combined with phrenic nerve stimulation to investigate the innervation of the diaphragm in dogs. They found that, contrary to widely held opinion, the muscle mass to the right of the esophageal hiatus was commonly innervated by both phrenic nerves, i.e., the right crus was bilaterally innervated in about one third of cases. However, they found no instance in which the left crus was bilaterally innervated.

Jefferson et al. (1949), who also worked with dogs, found complete paralysis of the left hemidiaphragm with left phrenicotomy. This (1) confirms the above findings and (2) confirms the teaching (which has been often challenged without adequate evidence) that the only innervation of the diaphragm is the phrenic nerve.

Sant'Ambrogio and Widdicombe (1965) have studied respiratory reflexes from the diaphragm and intercostals in rabbits to assess their strength. They used single unit EMG's as a direct and quantitative measure of activity before and after vagotomy. There is little doubt from their results that proprioception plays an important part in driving the respiratory muscles. Guttmann and Silver (1965) approaching the problem quite differently, i.e., by studying the reflex activity in the intercostals of tetraplegics, confirm the rôle of stretch reflexes in respiratory muscular activity.

Youmans and his group at the University of Wisconsin have been studying the "abdominal compression reaction" by means of emg records from the diaphragm and intercostal muscles of anesthetized dogs (Briggs et al., 1960). This reaction is initiated by procedures which cause a decrease in central blood volume

and it consists of a steady state of activity of abdominal muscles rhythmically interrupted by breathing. In some instances, the intercostal muscles show no action currents while in others they show a burst of activity during inspiration and again during the abdominal compression reaction. The steady-state contraction of the external oblique abdominal muscles commonly begins while expiration is in progress and reaches a maximum after completion of expiration. When a strong abdominal compression reaction is present, the initial phase of inspiration is the movement of the diaphragm caudally, related to sudden inhibition of the abdominal compression reaction and a corresponding decrease in intra-abdominal pressure. The diaphragm begins to move caudally because of less pressure on the abdominal side (and not because of motor activity) and it continues to move as a result of its contraction, according to Youmans and his colleagues (1963).

Delhez and various colleagues in Liège, Belgium, have made an important series of contributions to the literature of respiration and diaphragmatic function during the past several years (1963, et seq.). The amount of activity in the diaphragm in human subjects was found to comply proportionately with the ventilation up to 50 or 60 litres per min. Above that, emg activity rises more rapidly than the ventilation, apparently to counteract elastic forces and antagonistic activity (Delhez, 1964; Delhez et al., 1964a, b, c, d). Their insistence that strong diaphragmatic activity occurs during forced expiration has created considerable attention and controversy without satisfactory resolution as yet. Their views, expanded upon in a long review written by Petit, Delhez and Troquet (1965), are interesting; but fuller consideration is out of place here.

Motor Units in Diaphragm

Even in the highly developed human diaphragm, the muscle is quite thin and likely there is a great lateral spread of fibres belonging to one motor unit. To test this hypothesis, Krnjević and Miledi (1958) at the Australian National University in Canberra, investigated the distribution of single motor units in the rat dia-

phragm electromyographically using a "phrenic-hemidiaphragm" preparation. They found the fibres of one motor unit irregularly scattered over an area of several millimetres. They also found that the motor units were considerably intermingled (see also p. 9).

Accessory Respiratory Muscles

The muscles which are usually considered to be accessory respiratory muscles are the following: the muscles of the vocal cords (discussed on page 319); sternomastoid and scalenes in the neck (pages 288 and 334); abdominal muscles (page 273); pectoral muscles (page 162); serratus anterior (page 162); and trapezius (page 161). As I have pointed out in the appropriate sections of this book, the scalenes should be considered primary respiratory muscles, the abdominal muscles are certainly accessory respiratory muscles, and, generally, the upper limb muscles (including serratus anterior) take no part in quiet or even laboured respiration—except under highly abnormal conditions, diseases and postures (Grønbaek and Skouby, 1960).

Nieporent (1956) found that there was no activity in pectoralis major during quiet breathing, but during maximal inspiration some slight to moderate activity appeared. During dyspnea, pectoralis muscle functions primarily in inspiration as an accessory muscle. Campbell (1954, 1958) found some activity only during very deep inspirations in trapezius (upper part), latissimus dorsi, pectoralis major and minor, and serratus anterior. On the other hand, Tokizane et al. (1954), reported activity with ordinary breathing in some of these muscles, but, being unconfirmed by later studies, their findings are subject to serious doubt.

In patients with complete diaphragmatic paralysis, Hirschberg et al. (1962) found that most could breath quietly by using their accessory muscles. Surprisingly, the intercostals (whose viability could be proved by other tests) were the least active during quiet breathing; the abdominal muscles were the most active. Accessory muscles in the neck (although they were partially paralyzed in the patients with poliomyelitis) were also quite active. Of course, read-
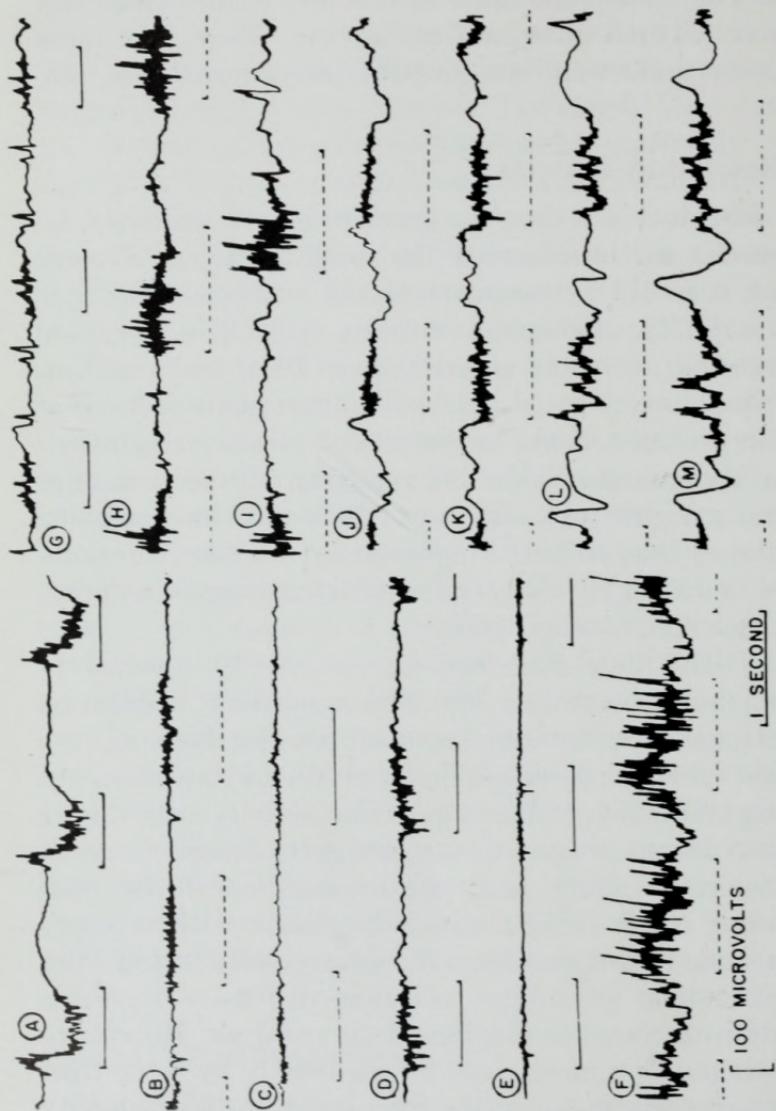
Fig. 136. EMG's of various canine muscles during respiration. Solid marker line—inspiration; dashed line—expiration. *A*, dilator naris; *B*, mylohyoid; *C*, sternohyoid; *D*, sternothyroid; *E*, hyothyroid; *F*, scalenus anterior; *G*, scalenus posterior; *H*, external intercostal; *I*, internal intercostal; *J*, rectus abdominis; *K*, external oblique; *L*, internal oblique; *M*, transversus abdominis. (From Ogawa *et al.*, 1960.)

ers of p. 288 would expect this. Guttmann and Silver's (1965) finding that the intercostals of tetraplegics resumed reflex activity is of some importance. This developed in response to stretch reflexes initiated by the diaphragm or the "accessory" muscles of the neck (mainly sternomastoid).

Ogawa *et al.* (1960) at Michael Reese Hospital in Chicago found in dogs that the following muscles had no respiratory function: digastric, masseter, levator nasolabialis, scutularis, cervicoauricularis, splenius, brachiocephalis, trapezius, rhomboideus, supraspinalis, infraspinalis, deltoid, semispinalis, serratus anterior, pectoralis superficialis and profundus, serratus posterior superior and inferior, and psoas. In contrast, they consistently found respiratory activity in the following canine muscles: nostril, intrinsic laryngeal, scalenus anterior, intercostals, rectus abdominis, external and internal obliques, and transversus abdominis (fig. 136).
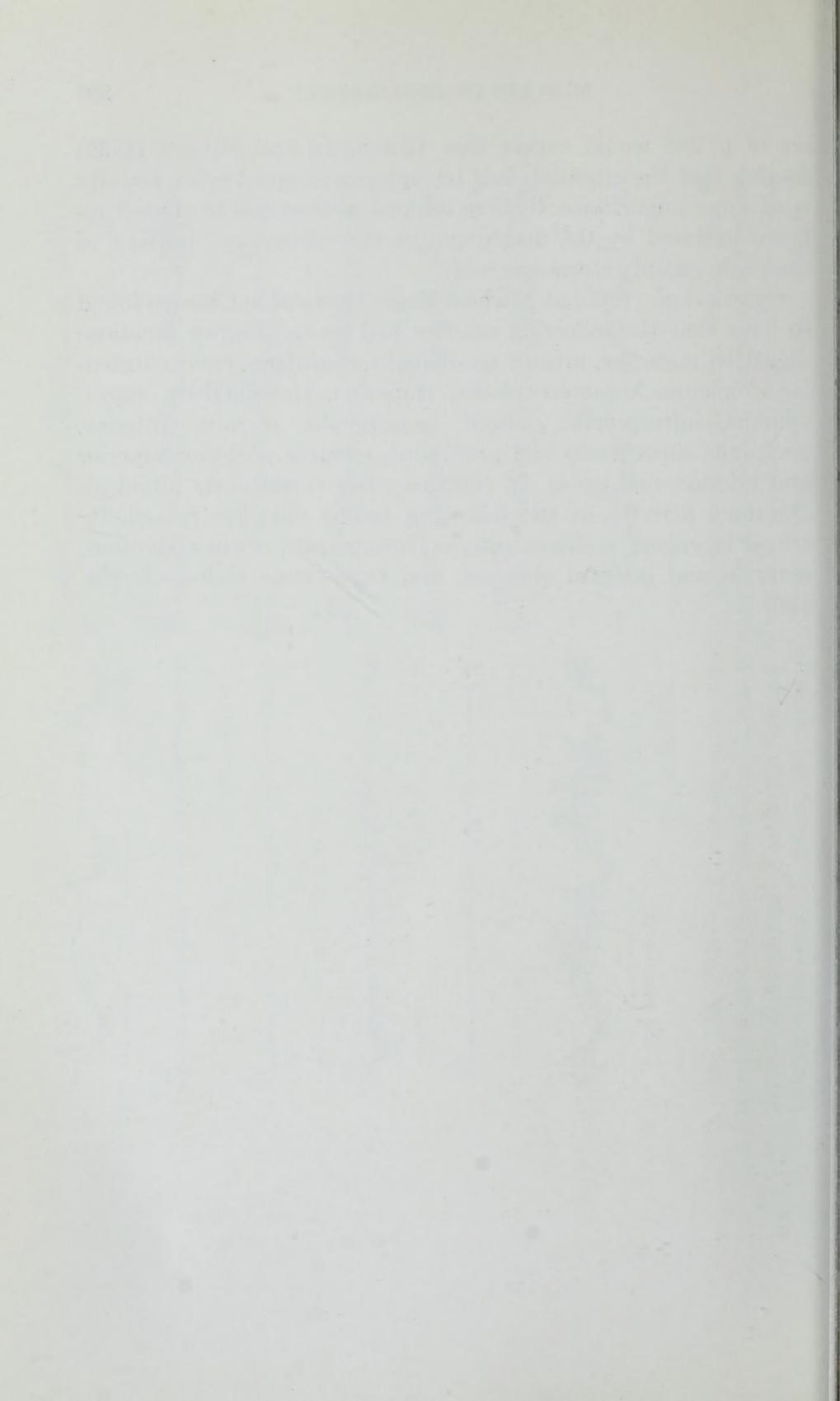
Mouth, Pharynx and Larynx

U NTIL 1958, electromyography of the mouth and pharynx was virtually an unexplored frontier, and even now the tongue— though it is an obvious and accessible muscular mass—has not been adequately explored. Indeed, I know of only one systematic study that has been done on the functions of the intrinsic or extrinsic muscles of the tongue. Furthermore, the easily accessible musculature of the floor of the mouth (i.e., mylohyoid, etc.) also has been badly neglected. On the other hand, the palate and the pharyngeal constrictors have now been well explored by several groups.

Insofar as the palate and pharynx are concerned, this chapter will deal chiefly with our own findings, supplemented by those of clinical electromyographers. Also to be discussed at the end are several controversial reports on the EMG of the larynx.

Tongue

Bole (1965), using our inserted, fine-wire electrodes described on p. 32, performed definitive studies of the actions of genioglossus muscle. He found that the right and left muscles act to-

gether with approximately similar emg response during many
general movements of the tongue—even lateral shifts. The greatest
emg activity appeared when the tongue met resistance. Surprisingly, little activity accompanied protrusion of the tongue unless
it was against the back of the incisor teeth.

Bole showed that there may be several different patterns of
glossal movement during swallowing. The duration of activity in
genioglossus ranged from 1.42 to 2.74 seconds and appeared in two
or more bursts. Generally the bursts were at the onset of swallowing and after the substance had left the tongue. Bole's pioneer
work on the human tongue deserves considerable following up and
gives great promise of revealing the functions of this vital organ.

Palate

Cho-luh Li and Arne Lundervold (1958), while working in
Montreal, had the opportunity of examining electromyographically a series of normal human palates as controls for a broader
study of cleft palates. They were able to record separately from
the tensor palati (which becomes aponeurotic as it turns around
the pterygoid hamulus into the palate) and the various fleshy
muscles in the palate itself. In our laboratory, we have performed
examinations of the soft palate in a series of rabbits (Basmajian
and Dutta, 1961a) and compared these with examinations in a
series of normal human volunteers (Basmajian and Dutta, 1961b).

[Extensive investigations by Doty and Bosma (1956) on dogs,
cats and monkeys were concerned chiefly with swallowing. These
investigators did not report on the soft palate as such (but see
below). Broadbent and Swinyard in 1959 reported on their emg
studies following human cleft palatal repairs in which they had
used a "dynamic pharyngeal flap." These studies are mentioned
here for the sake of completeness.]

Our emg experiments on the palate of rabbits were of two types.
In the first type, rabbits under general anesthesia were tested for
reflex swallowing with a bipolar needle electrode inserted into the
part of the palate that contains the bulk of levator palati. In the
second type of experiment, EMG's were recorded by two different
techniques in a series of conscious rabbits made to swallow "nor-

mally" by placing water on the tongue. Our experiments on human subjects were on conscious normal volunteers in whom recordings were made with special long, fine, bipolar electrodes inserted under direct vision into the levator palati.

In conscious human subjects, we always found, as did Li and Lundervold, a burst of activity upon inserting the electrode (fig. 137). This lasted for several seconds, but it never lasted more than 10 seconds in either our investigations or those of Li and Lundervold. Then complete relaxation of the levator palati and tensor palati ensued and continued for as long as the subject remained at rest. This was confirmed by Fritzell (1963) for both muscles by direct recordings. When our subjects sucked water through a straw, the levator palati became slightly active and remained thus as long as the water was held in the mouth (fig. 137).

During swallowing, potentials came as a burst lasting about $\frac{1}{3}$ second and followed by complete relaxation (fig. 137). Li and Lundervold comment only on the normal appearance of the potentials obtained during voluntary swallowing, but one gets the impression that their findings were similar to ours.

The results of our experiments on the soft palate of conscious
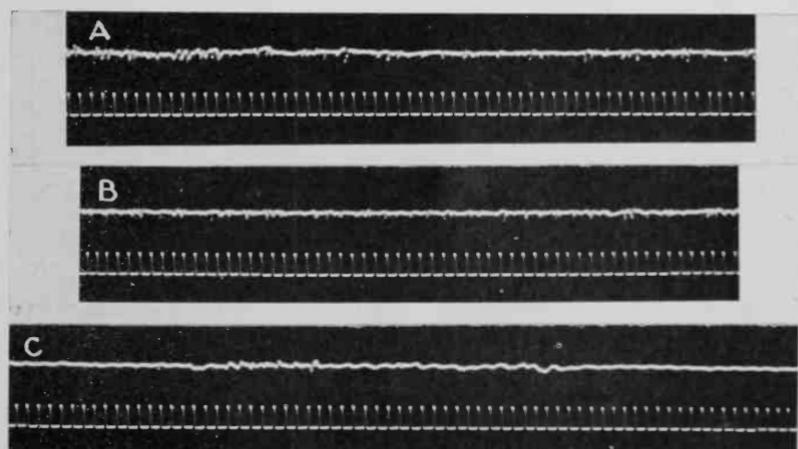
Fig. 137. EMG of human palate. A, "insertion" potentials; B, activity during sucking water through a straw; and C, swallowing. Calibration signal: 10-msec intervals; amplitude, ca. 500 μv.

rabbits were similar to those on the palates of human beings. In contrast, the most striking finding in anesthetized rabbits was that reflex swallowing (caused by prodding the pharyngeal mucosa) showed very little activity in the palate (see fig. 140 on p. 317).

Palatal Activity During Speech

Fritzell (1963) found that activity started simultaneously in tensor and levator palati just before speech begins. This "acoustically silent" period of palatal activity varied in different subjects. The potentials diminish and usually disappear before an utterance is finished.

When words beginning with a nasal sound are spoken, action potentials precede the microphone signal. But when nasal sounds appear within a word the potentials disappear or diminish only to return when oral sounds are made. "The production of nasal is regularly announced in the electromyograms before the sound appears in the microphone record," according to Fritzell.

Pharynx

In view of the relative inaccessibility of the striated muscles of the pharynx, electromyography of the sphincters has not been widely attempted. Nonetheless, a considerable number of publications that make reference to muscular action have appeared on the process of swallowing. In most of this material, no actual objective recordings of the sequence of events in the involved muscles have been reported. The recent resurgence of practical interest in the mechanism of swallowing and in the reparative surgery of the pharynx has made a bold approach to pharyngeal electromyography a necessity, So, Doty and Bosma (1956) performed emg studies of reflex swallowing in the areas of the mouth, pharynx and larynx of anesthetized monkeys, cats and dogs. Broadbent and Swinyard (1959) then made similar studies during operations on anesthetized human patients with cleft palate.

From the start of our own studies of the pharynx, we felt that we must not only examine reflex swallowing under anesthesia, but

also swallowing under conditions that are as normal as possible. Therefore, we devised various procedures towards that end, and we also performed extensive dissections to clarify the anatomy of the region. Our first report (Dutta and Basmajian, 1960) dealt with anatomical studies in rabbits. It was followed by a report on the EMG of the rabbit's pharyngeal and palatal muscles (Basmajian and Dutta, 1961a). Our third report dealt with emg studies on conscious, normal human beings (Basmajian and Dutta, 1961b).

In about half our series of rabbits, direct recordings with concentric needle electrodes were made of the electrical potentials of the soft palate and individual constrictors during reflex swallowing under anesthesia.

In the other half of the series, operative exposure was followed immediately by implanting into the three constrictors special indwelling, flexible, wire electrodes to be used for post-operative electromyography. Electromyographic testing was usually done after recovery from the operation—a delay of several days being the rule.

In some of the rabbits in which implants were used, simultaneous records were made also from the fleshy part of the soft palate *via* a concentric needle electrode. Active voluntary swallowing was induced by running some water from an "eye-dropper" onto the tongue of the rabbit.

In our studies of conscious normal volunteers, the electrodes were passed under direct vision through the open mouth, using a laryngeal mirror and clinical headset, when necessary. A special type of bipolar electrode was designed for use in these experiments. It consists of two fine surgical stainless-steel wires about 10 cm long, glued together, yet insulated from each other, by lacquer. This type of electrode has the advantage of strength, lightness and flexibility (figs. 138 and 139).

Except during obvious swallowing, in all the experiments on human beings, conscious rabbits and anesthetized rabbits, there is little or no activity in any of the constrictors. That is, there is no resting tonus.

During swallowing each constrictor of the rabbit contracts for
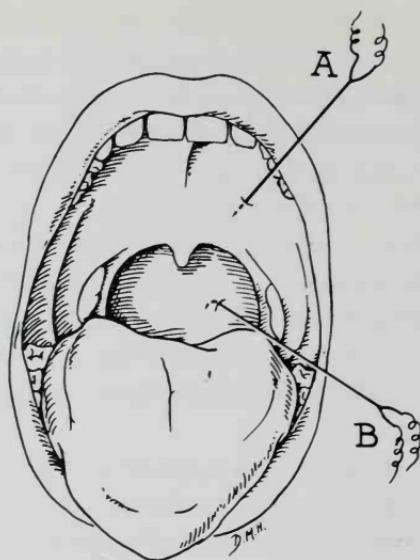
FIG. 138. Diagram of special bipolar electrodes, A, in soft palate and B, in pharyngeal wall.
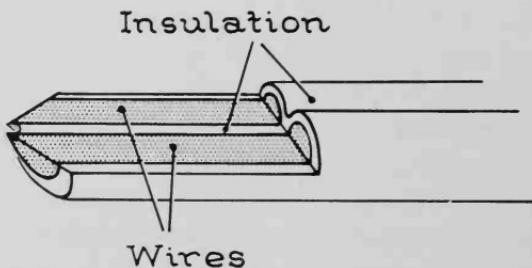
FIG. 139. Greatly enlarged cut-away diagram of tip of special electrodes (cf., fig. 138).

about $\frac{1}{4}$ second, whether it is part of reflex or of conscious swallowing (fig. 140). The contraction of the superior constrictor begins simultaneously with that in the soft palate; that in the middle constrictor is delayed by about 25 msec; and that in the inferior constrictor, by about 75 msec. The entire duration of activity in the constrictors lasts about $\frac{1}{3}$ second. These figures must be accepted as broad generalizations of our detailed results (Basmajian and Dutta, 1961a).

The amplitude of activity in the three constrictors of the rabbit gradually increases and becomes maximal just beyond the middle of its total period of activity. Then the amplitude falls to the base line due to rapid relaxation. It is important to note that the base line of *nil* activity is maintained except during swallowing, i.e., to repeat, there is no tonic activity of the palate and pharyngeal constrictor muscles. They act in an "all or none" fashion.

In the human volunteers, any activity picked up from these muscles following the insertion of the electrode apparently is a reflex "tightening up;" it can be abolished by the subject's voluntary relaxation. When the subject is relaxed and resting between swallows, the pharyngeal constrictors are inactive, as is the levator palati. During the sucking of water through a straw, all three constrictors remain silent, while—as might be expected—the levator palati is active. With each swallow, the duration of activity is very close to a $\frac{1}{2}$ second in each of the pharyngeal constrictors (fig. 141).

Because we did not make recordings in the human muscles simultaneously (as we did in our study on rabbits) we cannot say what the exact sequence of activity is in man. However, there is no reason to suppose that it is different from that in rabbits.

Doty and Bosma (1956) described the emg pattern of activity
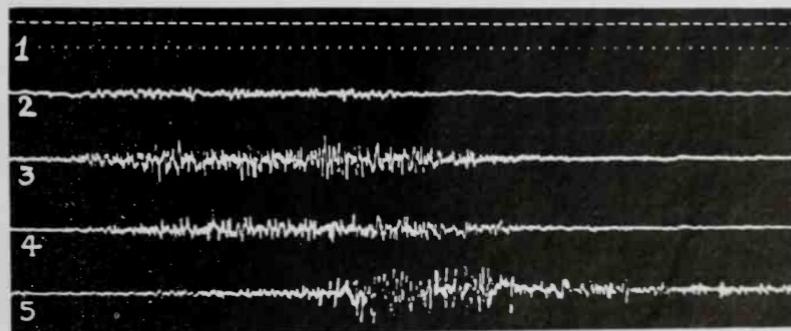
Fig. 140. Simultaneous EMG's during swallowing in the rabbit. *1*, calibration: 10-msec intervals; amplitude, ca. 300 μv; *2*, soft palate; *3*, superior constrictor; *4*, middle constrictor; and *5*, inferior constrictor. (Tracings slightly retouched to improve engraving.)
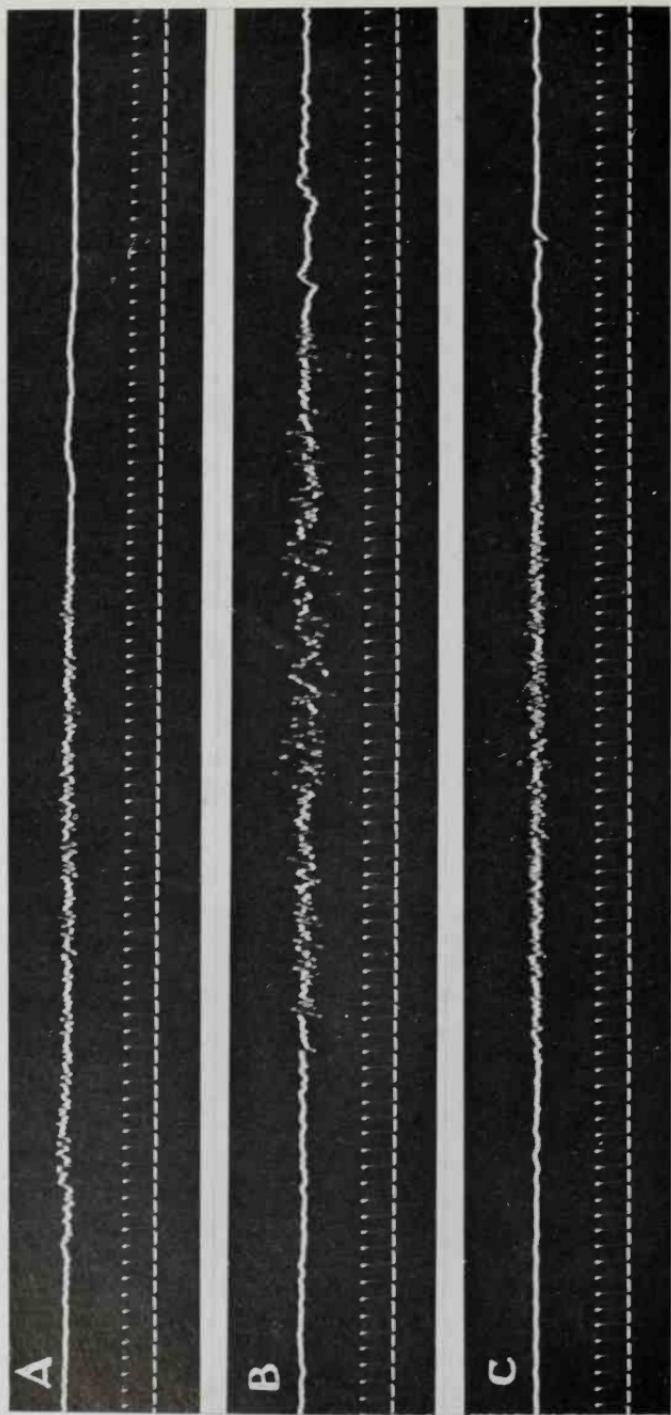
Fig. 141. EMG's of human pharyngeal constrictors: *A*, superior; *B*, middle; and *C*, inferior

during swallowing in the muscles of the mouth, pharynx and larynx of monkeys, cats and dogs. They found a definite pattern or sequence of activity, i.e., with minor variations, the "schedule of excitation and inhibition among the participating muscles was highly constant." No difference was found in reflex swallows evoked by various means including stimulation of the superior laryngeal nerve, stimulation with a cotton swab or the rapid squirting of water into the pharynx. A leading "complex," consisting of the superior constrictor, palatopharyngeus, posterior intrinsic muscles of the tongue and various muscles attached to the hyoid bone, becomes active for $1/4$ to $1/2$ second to initiate the act. The middle constrictor, inhibited at first (as in our experiments), follows. The inferior constrictor is the last to become active, being deferred until the leading complex is nearly over (fig. 142).

Rather similar findings in dogs have been reported by Kawasaki *et al.* (1964) whose studies of air pressure gradients is particularly valuable.

Cricopharyngeus muscle has been the special concern of Levitt, Dedo and Ogura (1965) of St. Louis, who have recently made the greatest contribution to its understanding. In dogs they found that these sphincteric fibres at the junction of pharynx and esophagus relax much of the time, contrary to the widely held view that they are tonically contracting. Bursts of activity do occur but usually in response to external factors such as breathholding, straining or stimulation of the hypopharynx.

Larynx and Vocal Cord

As Professor Georges Portmann of Bordeaux and Paris pointed out in his Semon Lecture (published in 1957), the larynx has two functions. The first comprises respiration and the protection of the pulmonary apparatus, these being inseparable. The other is phonation or the production of sound. Suprisingly, to the present time only provocative results have been obtained by electromyography for this vital function. Serra (1964) has given a thorough review of the various neuromuscular studies of this area.
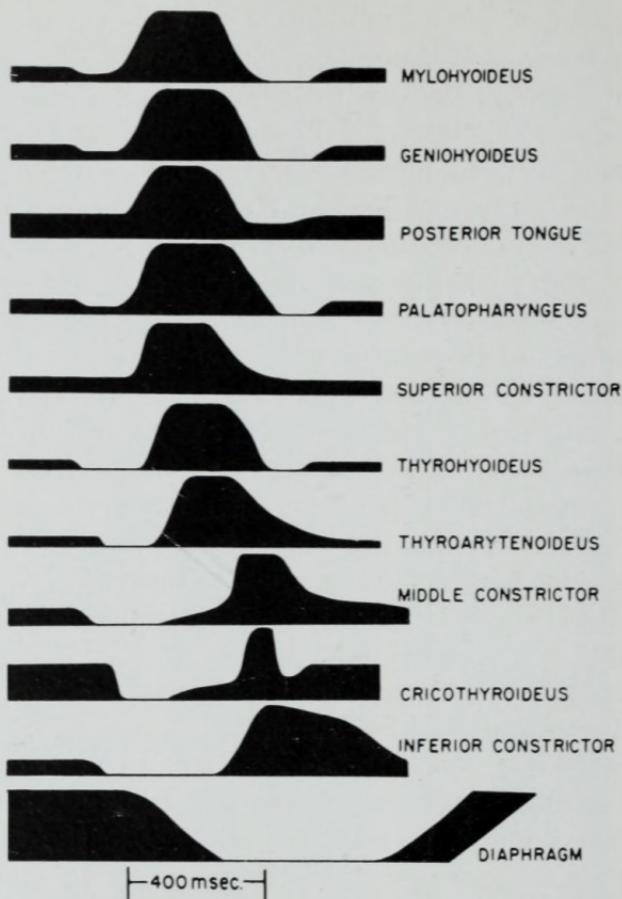
FIG. 142. Doty and Bosma's (1956) schematic summary of emg activity during swallowing in dogs.

Portmann and his colleagues have made some important contributions through their experiments on patients who had had operations that left the glottis exposed post-operatively. These investigators were able to insert needle electrodes directly into different parts of the vocal folds and the thyroarytenoid muscles.

During each expiration, the thyroarytenoid becomes very active, especially in the middle of expiration. At the beginning of inspiration, activity stops and does not reappear until expiration

begins. Spontaneous and involuntary activity during expiration is quiet independent of every effort of phonation.

Portmann insists that during phonation the electromyographic oscillations have the same frequency as the sound emitted (see fig. 143). In low pitched speech, he found the frequency to be 60 per second, and in high pitched "soprano" sounds, over 1300 per second. From these findings, Portmann and his colleagues believe that the frequency of vibration must be related to the neural frequency in the laryngeal nerves. This was strong support for the theory advanced by Husson (1950).

Not all specialists in this field agree with Portmann, however. Some strongly disagree, and they have good contradictory evidence (Rubin, 1960; Spoor and Van Dishoeck, 1960; Kirikae
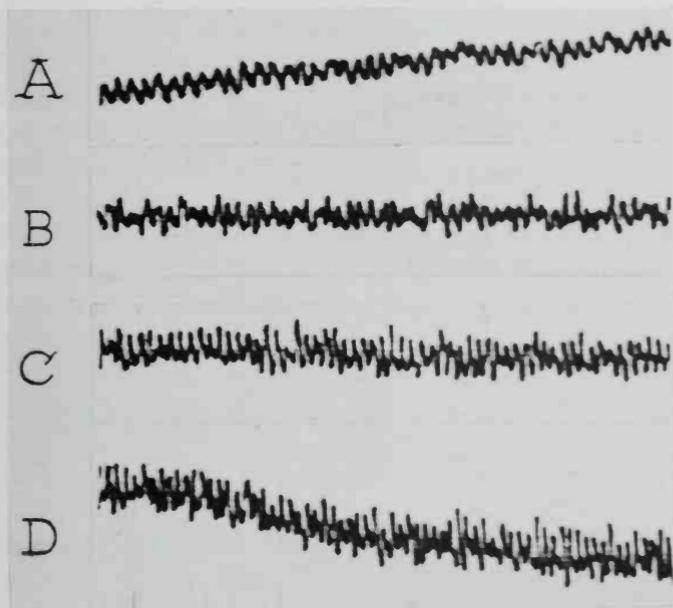
Fig. 143. EMG of vocal cord during phonation of rising tones. Rising basic emg frequency (tracings A to D) from different musical sounds: "do" or "ut" in A, through "mi" and "fa" in B, "fa"-sharp in C, and "la" in D. (From Portmann et al., 1956.)

et al., 1962; Milojevic and Hast, 1964; Dedo and Ogura, 1965; and still others). According to Floyd, Negus and Neil (1957) closure of the glottis is caused by tonic coordinated action of the sphincteric muscles in which thyroarytenoid plays its part. They have not succeeded in reproducing in dogs a higher frequency of vibration of the cords by stimulation of the laryngeal nerves with graded electrical frequencies. Therefore, Portmann's concept of clonic activity of the laryngeal muscles requires further confirmation to withstand the gale of scepticism that it has caused. Certainly it provides difficulties yet to be explained.

My impression is that the Portmann-Husson theory that relates vibration frequencies to nerve-impulse frequencies has a shaky future. Perhaps this is too cautious a statement, but one cannot abandon the theory entirely so long as there is evidence being produced by independent workers which shows that complete tetanic fusion does not occur in laryngeal muscles until stimulation frequencies as high as 400 cps are used (Mårtensson and Skogland, 1964). At the very least, the theory has reawakened a great deal of very lively interest in a vital function, and therefore has served a very useful purpose.

Green and Neil (1955) noted that impulses in the recurrent laryngeal nerve of cats coincide with inspiration and emg activity in the posterior cricoarytenoid. They found emg activity in the abductor muscles of the cords during inspiration alternating with activity in the adductors during expiration.

Under the general direction of Fritz Buchthal of the Institute of Neurophysiology at Copenhagen, Faaborg-Andersen completed a monumental study on the normal and abnormal muscular control of the vocal cords and published it as a monograph in 1957. In a long series of normal persons, he inserted needle electrodes under direct vision into the cricothyroid, vocalis, arytenoideus, thyroarytenoid and posterior cricoarytenoid muscles, two at a time, and recorded the subject's phonation simultaneously on a tape recorder.

At rest, there was a slight activity in all the adductors even if the breath was held quietly. This then is "postural activity,"

according to Faaborg-Andersen. It increased from the resting level during inspiration but was unchanged during expiration. At "rest," the abductors were very active by contrast; but during the inspiratory phase this activity decreased somewhat, although it was uninfluenced by expiration.

With phonation, an increase in electrical activity was found in all the adductor muscles. The change began 0.35 to 0.55 seconds before the audible sound. Unlike Portmann, Faaborg-Andersen found that single unit potentials fell below the range of 20 to 30 per second in basic frequency. This is much like ordinary skeletal muscles.

During phonation with increasing pitch there was no corresponding increase in the electrical activity of the adductor muscles. However, with increasing pitch the increase in the total electrical activity was marked provided that the increase in pitch was in the same register, i.e., within the same octave. If the increase in pitch was accompanied by a shift in register, the change was only slight.

Thus Faaborg-Andersen does not support the theory that the frequency of vibration of the vocal cords during phonation of a tone changes directly with the frequency of nerve impulses and contractions of the muscle fibres. His finding of basic frequencies cannot be dismissed and it certainly does not agree with Port-
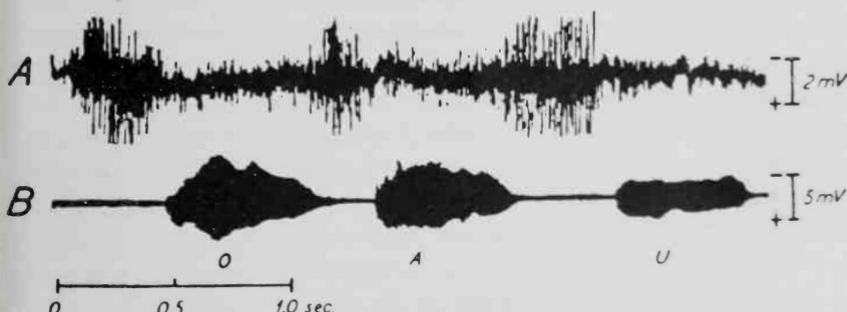
FIG. 144. EMG in thyroarytenoid (*tracing A*) and microphone recording (*tracing B*) during phonation of vowels o—a—u at frequency of 200 cps. (From Faaborg-Andersen, 1957.)

mann. Faaborg-Andersen upholds the orthodox view (not yet completely proved because the present discrepancies in research results have not been resolved) that the vibrations of the vocal cord are passive and independent of the frequency of motor unit contractions.

With phonation of different vowels there was no apparent electromyographic change in Faaborg-Andersen's series (fig. 144). With whispered voice or "silent speech," there was activity in the adductor muscles but it was far less than with ordinary voice.

Buchthal and Faaborg-Andersen (1964) found that the average time between the onset of the increase in electrical activity in cricothyroid muscle and the onset of phonation is between $\frac{1}{10}$ and $\frac{1}{5}$ of a second. The interval may be considerably shorter for some sounds.

During a cough and during swallowing there was a considerable increase in the electromyographic potentials in all the adductors just before the onset of audible sound; conversely, the abductors relaxed during the cough.

In conclusion, we can only hope that renewed and vigorous emg research will soon eliminate the controversy about this important region.

Laryngeal Muscle Training

As this book goes to press, Hardyck *et al.* (*Science*, *40:* December, 1966, p. 1467) report that auditory emg feedback from laryngeal muscles has proved highly successful in treating persons whose silent reading is greatly slowed by subvocalization.

Muscles of Mastication, Face and Neck

Muscles of Mastication

THE first concerted effort to apply electromyography to problems of orthodontics and normal temporomandibular physiology was made by a dentist, Robert Moyers, while working as a graduate student at Iowa. Upon his becoming Professor of Orthodontics at the University of Toronto in 1949, I had the privilege of being associated with him and of seeing his work first-hand. Following his lead, other workers have published a number of good studies although some of them have disagreed with certain details of Moyer's earliest work (1949 *et seq.*). The following account is a review of the published reports in the field. I have also drawn upon a number of special sources including the research of graduate students.

Temporalis

RESTING TONUS. Moyers (1949, 1950) reported for normal subjects a "remarkably even state of *tonus*" in all three parts of the muscle when it is at rest, stating also that the normal maintenance of mandibular posture is shared by all the parts. Carlsöö (1952), although he agreed that temporalis is the main postural muscle in the habitual rest position, insisted that the posterior part of temporalis was the more important part in this position. MacDougall and Andrew (1953) also agreed that resting postural tonus was obtainable, but they were less precise.

Latif (1957), while working under my direction, made a definitive emg study of both temporalis muscles in 25 normal teenage children. In the physiological resting position of the mandible in the upright subject, both the anterior and posterior fibres of temporalis were continuously active in almost all the subjects.
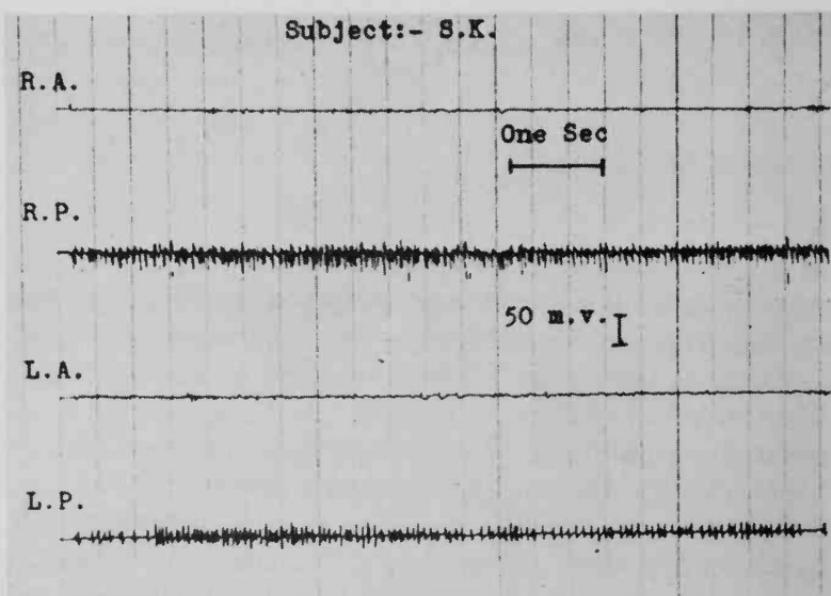
FIG. 145. EMG's of anterior and posterior parts of right and left temporalis muscles at rest show much greater postural activity in posterior parts (R.P. and L.P.) compared with anterior (R.A. and L.A.). (From Latif, 1957.)

However, this activity was much greater in the posterior fibres (fig. 145), as hinted at by Carlsöö's earlier findings and in contradiction to those of Moyers. In the same year, Latif's finding was duplicated independently by Kawamura and Fujimoto (1957) of Osaka.

END-TO-END OCCLUSION (INCISOR BITE). All parts of temporalis were active, the greater activity being somewhat more frequently in the anterior fibres (40% of muscles), but in many (22%) the posterior fibres predominated, while in a third of the muscles the activity was equal throughout (fig. 146). In several muscles, in contrast, the temporalis was inactive with incisor bite, even though this condition was considered to be the norm (quite erroneously) by Keith (1920). These results of Latif confirmed the findings of MacDougall and Andrew (1953).

MOLAR OCCLUSION. All the fibres of the temporalis showed marked activity in all subjects, as would be expected (fig. 147). This is the chief function of the temporalis.
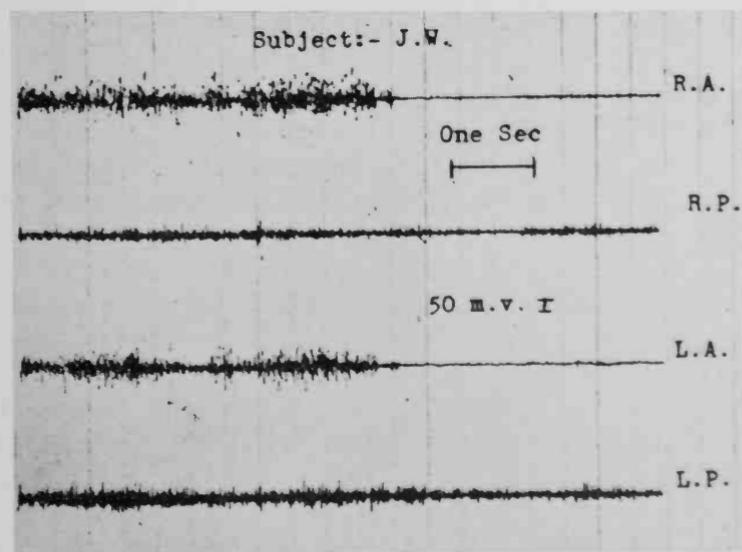
FIG. 146. EMG's of temporalis muscles during end-to-end occlusion from right anterior (R.A.), right posterior (R.P.), left anterior (L.A.) and left posterior (L.P.) parts. (From Latif, 1957.)
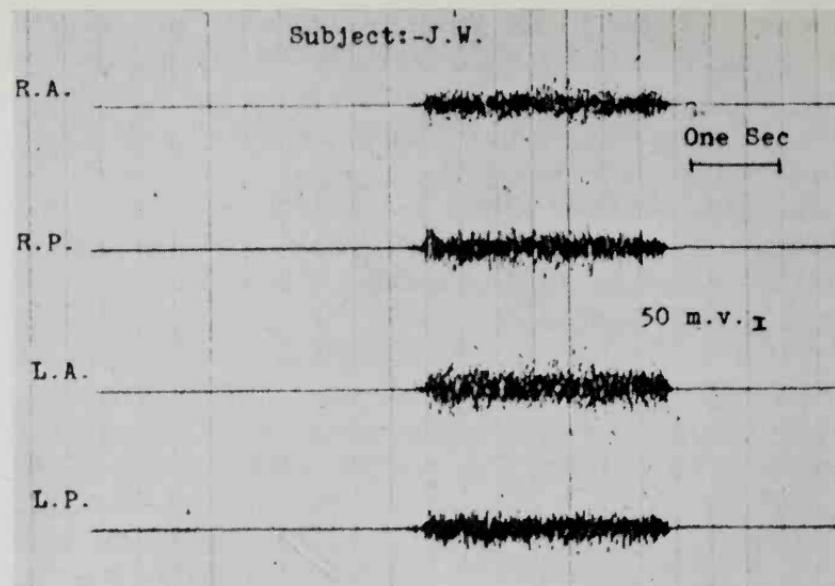
Fig. 147. EMG's of temporalis muscles during molar occlusion from right anterior (R.A.), right posterior (R.P.), left anterior (L.A.) and left posterior (L.P.) parts. (From Latif, 1957.)

RETRACTION OF THE JAW. A universal finding was a marked activity in the posterior fibres of temporalis with lesser activity in the anterior fibres during the drawing back of the jaw from the protruded (protracted) position. This is in keeping with the accepted teaching.

PROTRACTION. Latif's findings were not in agreement with the opinion of McCollum (1943) and the findings of Moyers that the anterior fibres are active during protraction. He found *no* activity, as did Carlsöö, MacDougall and Andrew, and Woelfel *et al.* (1960). Indeed the activity even dropped from the resting tonus (fig. 148). Apparently the temporalis shifts the burden of supporting the jaw to the muscles that protrude it, chiefly the lateral pterygoids.

LATERAL MOVEMENTS. Moyers' findings that the temporalis abducts the mandible was clearly confirmed by the observation that this action is almost universal (fig. 149). In repetitive side

to side movements, first one temporalis and then the other acts, each pulling the mandible only to its own side.

DEPRESSION. During ordinary opening of the mouth, temporalis is inactive (MacDougall and Andrew, 1953; Latif, 1957). When the mandible is forcibly depressed (maximal opening of the mouth) some irregular muscle potentials do appear, suggesting that temporalis acts then as a protector against dislocation of the jaw.

The following paragraph summarizes the functions of temporalis. It maintains mandibular posture in the physiological resting position, the posterior fibres taking a more active part than the anterior. Its chief function is molar occlusion, and it is an ipsilateral abductor (and therefore a contralateral adductor) of the mandible. During maximal opening of the mouth, the temporalis acts as a preventative to dislocation but it plays no rôle either in ordinary opening of the mouth or in protraction of the jaw. In end-to-end occlusion (incisor bite) the anterior fibres are more active.
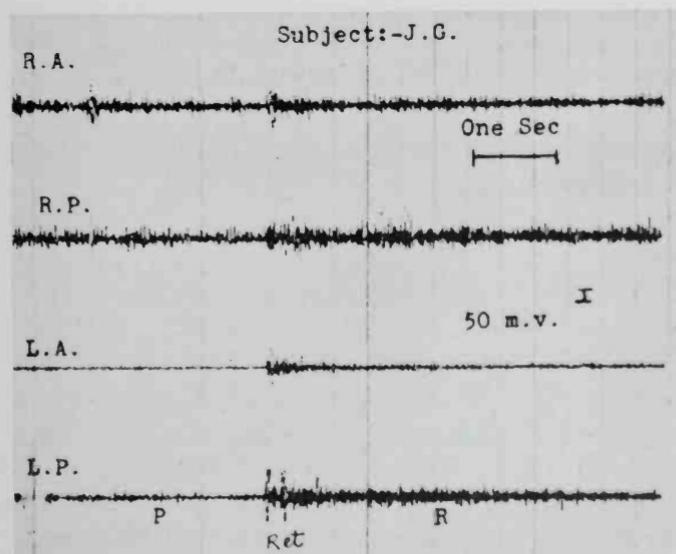
FIG. 148. EMG's of temporalis muscles during protraction of mandible (P.) and at rest (R.). Ret. = retraction. R.A. and R.P., from right anterior and posterior, L.A. and L.P., from left. (From Latif, 1957).
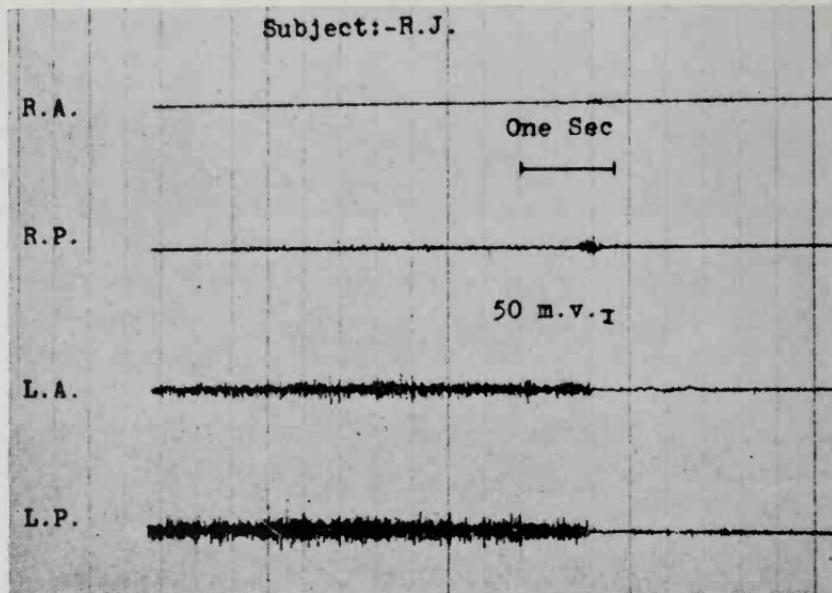
FIG. 149. EMG's of temporalis muscles during "left lateral position" of mandible. Note greatest activity in left posterior (L.P.) fibres, and least in right anterior (R.A.). (From Latif, 1957.)

The temporalis retracts the protruded jaw, the posterior fibres being especially active.

Masseter

As would be expected, during forceful centric occlusion the masseter muscle is very active (Pruzansky, 1952; Moyers, 1950). During chewing movements, the maximal activity occurs in the masseter about the time the jaw reaches the temporary position of centric occlusion. Masseter is not an important postural muscle in the habitual resting position (Carlsöö, 1952), though it does show some activity in its superficial part during protrusion and increasing activity with increasing weights (fig. 150). It also acts as an ipsilateral abductor of the mandible. MacDougall and Andrew found that its deep fibres are occasionally active during retraction.
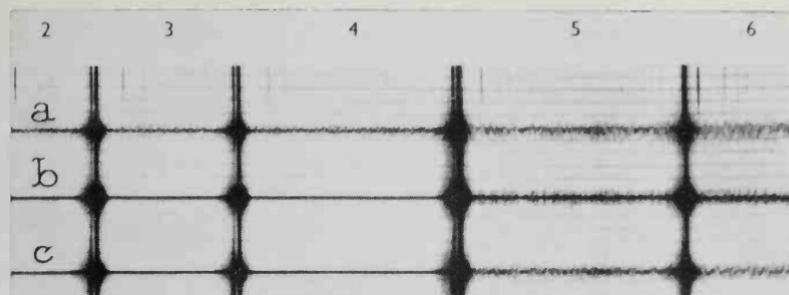
FIG. 150. EMG's from a, posterior part of temporalis; b, superficial part of masseter and c, medial pterygoid, with progressively increasing loads starting at "2." (From Carlsöö, 1952.)

Medial Pterygoid

During simple protraction, Moyers always found strong activity with needle electrodes in medial pterygoid. This decreased slightly if the mandible was depressed while being protracted. Unilateral contractions of the muscle accompanied (caused ?) contralateral abduction of the chin and was particularly impressive when there was an added element of protraction (Moyers, 1950; Carlsöö, 1952).

Lateral Pterygoid and Digastric

During mandibular depression, Moyer (1950) found that the first large potentials to appear are in the lateral pterygoid and the activity reaches its peak even before the other muscles become active (fig. 151). Furthermore, it continues throughout the movement. Woelfel et al. found the lateral pterygoid very active in contralateral excursions, uncontrolled openings and protrusions of the mandible. However, it was inactive during hinge openings of up to 1 cm. Apparently its function is to draw forward the articular disc in the temporomandibular joint along with the head of the mandible.

During mandibular depression, the digastric muscle comes into action after the lateral pterygoid and is not as important. However, its action is essential for the maximum depression of forced
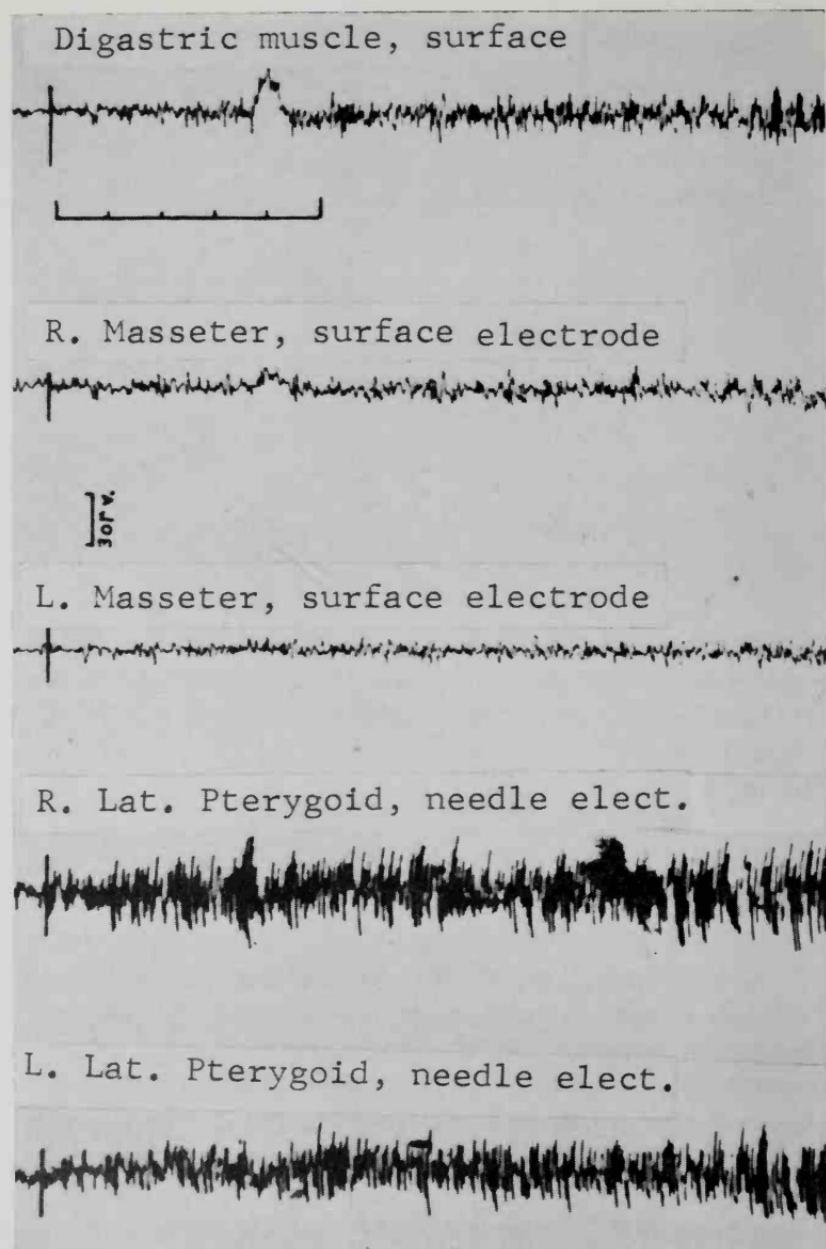
Fig. 151. EMG's of mandibular depression. (From Moyers, 1950.)

or complete opening of the mouth. The right and left digastric muscles do not function as individuals. They contract bilaterally with greatest activity during uncontrolled openings and retrusions of the mandible (Woelfel *et al.*, 1960).

Co-ordination during Chewing

Using subcutaneous wire electrodes, Ahlgren (1966) studied the muscular coordination and emg activity during chewing of peanuts and of chewing-gum. Considerable variation of patterns from subject to subject was a salient finding. The commonest pattern during gum-chewing (in 44%) was one in which the ipsilateral temporalis contracts first, then the contralateral temporalis and both masseters simultaneously. The peak of activity and the ending of activity occurs simultaneously most of the time. With peanut-chewing, the commonest pattern was both masseters and temporalis contracting simultaneously.

Summary of Mandibular Movements

The various movements of the jaw are produced by cooperative activity of several muscles bilaterally or unilaterally. Mandibular elevation is performed by the temporalis, masseter and medial pterygoids and depression by the lateral pterygoids and digastrics. The digastrics show their greatest activity in forceful opening of the mouth at the limit of depression of the mandible. Lateral movements are performed by the ipsilateral temporalis and masseter and the contralateral medial pterygoid (and, to a lesser extent, the lateral pterygoid). Protraction is performed by the medial and lateral pterygoids while retraction is by the temporalis, chiefly its posterior fibres, and perhaps the deep part of masseter.

Muscles of Facial Expression

Systematic electromyography of the muscles of expression has been neglected, although clinical electromyographers are constantly concerned with facial palsies. To my knowledge no organized study of normal function has been done in this field, perhaps because the muscles are so superficial and their isolated

actions seem to be apparent. Nonetheless, because of their special clinical importance, we ought to know more about the actions of buccinator and the muscles of the lip. (Orbicularis oculi has been investigated with the eye muscles; see p. 346.)

Mentalis muscle, which wrinkles the chin, was the subject of an investigation primarily concerned with its reactions during sleep. Hishikawa, Sumitsuji, Matsumoto and Kaneko (1965) of Osaka, showed a fairly continuous "tonic" activity of mentalis in man except during deep sleep when it relaxes completely for short periods.

[DePalma, Leavitt and Hardy (1958) made a brief electromyographic study of the lip musculature in full thickness flaps that had been rotated by plastic surgery from the upper to the lower lip to fill a wedge-shaped defect. In four patients, there was regeneration and reinnervation of the motor nerve to the flap with return of apparently normal function. A similar study has been reported in Sweden by Isaksson *et al.* (1962).]

Neck Muscles

Platysma

The first and probably the only careful study of this broad sheet of subcutaneous muscle was done by de Sousa (1964) who investigated 20 men using needle electrodes. The obvious actions of this rather obvious muscle produced the greatest activity (pulling the thoracic skin up and the angle of the mouth down).

During abrupt inspiration (but not expiration) there was activity that de Sousa interprets as helping to reduce the constricting effect of the skin on the subcutaneous veins of the neck. Widening the opening of the mouth ("buccal rima") elicited marked activity, but the natural opening of mouth and jaws did not. Active and resisted movements (flexion, extension and rotation) of the neck did not recruit platysma, nor did swallowing.

Sternomastoid and Scalenes

The sternomastoid and the scalenes are undoubtedly muscles of respiration whether we agree with Campbell (1955b) that they

are accessory or with Jones *et al.* (1953 *et seq.*) that they are primary. Certainly, the scalenes are active during inspiration with even quiet breathing and Campbell found them active in coughing and in other severe expiratory efforts. He found the sternomastoids active only with deep breathing (see also p. 289).

Hishikawa *et al.* in the study mentioned above also studied the suprahyoid muscles; again they found tonic activity except during deep sleep.

Longus Colli and Longissimus Cervicis

Using the technique of inserted fine-wire electrodes, Fountain, Minear and Allison (1966) have revealed the normal functions of these deeply seated muscles in man. Ultimately they believe their work will serve as a baseline for studies of injuries and spasms in the neck. The same group has also investigated the longus colli in the dog.

When the human subject is sitting or standing in a relaxed position, both longus and longissimus cervicis are almost completely inactive. This is in keeping with most postural responses in the human erect trunk. The same is not true in the dog unless the head is supported externally.

Longus colli is a strong flexor of the cervical spine, acting reciprocally with the longissimus, a strong extensor. Both muscles are synchronously active during rotation. Influences on lateral bending of the neck appear to be minimal, contrary to widespread belief. Most surprising and interesting is a pronounced increase in activity in longus colli during talking, coughing and swallowing. Apparently this represents a reflex stabilizing of the neck during pharyngeal contractions.

NECK MOVEMENTS. The slightest attempt of a supine subject to raise his head from the couch is accompanied by marked activity in the sternomastoid and scalenes. This was the finding of Campbell (1955) and I have also confirmed this in scattered observations.

No other systematic reports are available on the activity of these muscles as demonstrated electromyographically. However, Hellebrandt *et al.* (1956) published an account of their research

on the tonic neck reflexes in "exercises of stress" in human subjects. This group had noted previously that spontaneous ipsilateral head-turning occurred regularly during unilateral wrist-extension in hypertonic neurological conditions. From their study they concluded that exercise against resistance calls upon synergists which may be far removed from the part exercised. The pattern of concurrent action in the neck that developed as a result of stress in exercising the upper limb is sufficient to modify the position of the head. Following this discovery, the use of strong voluntary head-movement in the direction of the spontaneous positioning was tested; it appeared to augment the output of work. Therefore, this reflex positioning of the head does, in fact, appear to help the normal work of the upper limb.

Other Neck Muscles

Trapezius was discussed with the upper limb in Chapter 9 (p. 161), the laryngeal muscles in Chapter 16 (p. 319) and digastricus earlier in the present chapter with the muscles of mastication (p. 331). No systematic studies have been reported on the infrahyoid musculature.

CHAPTER *18*

Extraocular Muscles and Muscles of Middle Ear

Extraocular Muscles

ALTHOUGH Scandinavian, Japanese and Italian workers have also published in this field, most of the ocular electromyography that has received wide attention has been done by several small groups of investigators in the U. S. A. The two most prolific groups are located in San Francisco and New York City. The former includes Marg, Tamler, Jampolsky and other occasional associates; the latter is centred on one investigator, Goodwin M. Breinin. Of necessity, this chapter will be entirely a review and synthesis of the work of these and other investigators, for I have had no extensive experience with the extraocular muscles.

Before proceeding further, it must be clear that *electro-oculography*, which is sometimes confused with electromyography, is distinctly a different technique and therefore is not the subject of our present chapter. Electro-oculography is recorded through superficial skin electrodes in the region of the orbit and consists of potentials arising in the retina, extraocular muscles and other

337

sources in the orbital cavity. With a venerable but rather dull history dating back about a century, it has continued to show more promise than results. (For an excellent summary of electro-oculography, see Marg, 1951.)

Electronystagmography is related to electro-oculography. It depends on the existence of a corneo-retinal electrical potential that varies with the eye movements during nystagmus. It, too, is beyond the scope of this chapter: for a good review, see Milojevic (1965).

Electromyography of the muscles that move the eyeball is a comparatively recent development and uses direct recording of motor unit potentials from these muscles. Jampolsky *et al.* (1959) warn, with proper alarm, against attempts to measure relative strength of extraocular muscles by using only the amplitude of potentials as the criterion, because there are many sources of emg artifact. Variations in the structure of the muscles being tested and in the positioning of the electrodes can also lead to errors.

Normal Position and Movement of the Eyeball

Several groups have shown that the recti exhibit fairly strong, persistent activity to maintain the position of the eye during waking hours. We may conclude, then, that positioning results from a balance of activity among these muscles. Björk and Kugelberg (1953) demonstrated a persistence of this activity even in darkness.

These last-named workers also showed that each change of ocular fixation is accompanied by a gradual increase of activity in the prime mover or agonist with a reciprocal decrease in the antagonist whether the movements were slow or fast. With extreme positions of gaze, e.g., far to one or other side, the antagonist is usually completely inhibited.

During fast movements, there is a complete inhibition of the antagonist accompanying the sharp short burst of activity in the agonist (fig. 152). During a saccadic eye movement, Tamler, Marg, Jampolsky and Nawratzki (1959) found a heightened burst
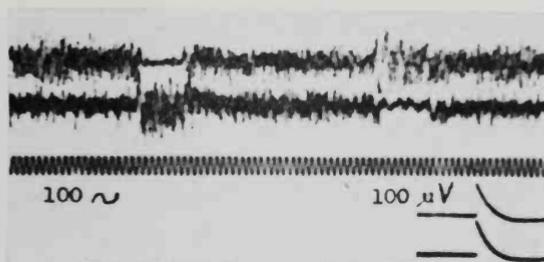
FIG. 152. EMG's from lateral rectus (*upper tracing*) and medial rectus of one eye during quick changes of fixation from 10° outward to centre of scale and back to 10° outward. There is abrupt inhibition in the antagonist simultaneous with increase in agonist activity. (From Björk and Kugelberg, 1953.)

of activity in the agonist, inhibition of the antagonist, and co-activity of the auxiliary muscles. A saccadic eye movement is a type that occurs in changing the gaze from one point in space to another and includes small terminal oscillations. Tamler *et al.* confidently assert that rapid movements of this sort are not ballistic in nature (see Chapter 7, p. 127). Miller's (1958) independent findings would seem to agree (fig. 153), although he states that for large movements one or more bursts of activity, in addition to the initial burst, may be found. Nonetheless, the antagonist remains completely inhibited.

Robinson (1965) has shown that both smooth pursuit and sac-
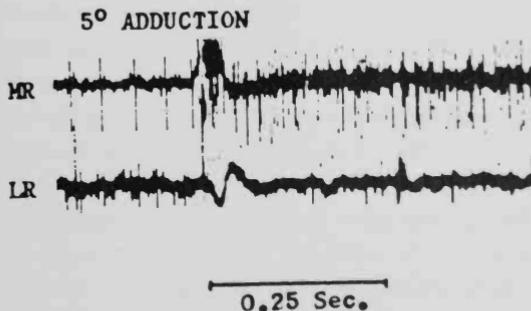
FIG. 153. EMG's from medial and lateral rectus during a 5° saccadic movement. (From Miller, 1958.)

cadic movements may occur with complete temporal independence. Smooth movements may occur just before, after or with saccadic ones.

There seems to be no doubt, then, that the muscles of the eye are in more-or-less continuous activity except during sleep (see below). Indeed, their rôle may be compared best to dynamic guy-wires.

Position of Ocular Rest

Among oculists, the position of the eyes during sleep and anesthesia has been the subject of much interest, speculation and investigation. Reported observations have been conflicting and sometimes confusing. During anesthesia, for example, different degrees of vergence have been reported, as well as versions during the induction stage. In surgical anesthesia, the movements cease and during the asphyxial stage of anesthesia, a convergent depressed position may be assumed. A similar behaviour may be noted during sleep (Breinin, 1957 *et seq.*).

According to Breinin (1957b), the disappearance of esotropia during anesthesia is a frequent observation, with straight eyes or divergence taking the place of esotropia. While investigating the electromyographic changes during anesthesia and sleep, Breinin found that the "innervation" to all horizontal recti rapidly decreased during the induction of general anesthesia with intravenous Pentothal in a patient with intermittent exotropia. When the surgical plane was reached, all nerve impulses were repressed and the eyes occupied a moderately divergent position. As the level of anesthesia lightened, individual motor units appeared. When the plane of anesthesia was again deepened, the motor units disappeared promptly. Therefore, the position of the eyeball during surgical anesthesia suggests that the motor nerve impulses to the extraocular muscles cease completely.

The position of the eyeball during anesthesia is apparently dictated by anatomical-mechanical factors—bony, fascial and muscular—and represents the anatomical position of rest. It is, then, the *basic* position which is modified by the normal factors of motor innervation during consciousness. If this basic position
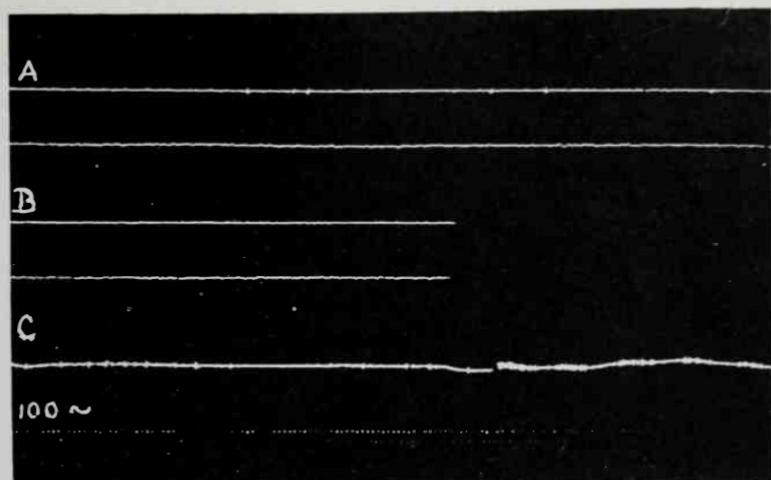
Fig. 154. *A* and *B*, EMG's (*upper tracing in each case*) with simultaneous electro-oculograms of medial rectus during sleep. Tracing *C*: shows resumption of normal waking pattern (toward its right end). (From Breinin, 1957b.)

is one of divergence, then a basic stress toward divergence must underlie whatever position the eyes assume in consciousness, according to Breinin. "It opposes esodeviation and facilitates exodeviation." The frequency of divergence under surgical anesthesia supports the concept of a basic anatomical divergence, to which, in exotropia, may be added innervational divergence.

During the light dozing phase preceding ordinary sleep, very irregular discharges and bursts of potentials appeared in Breinin's investigations. He reports that a run of double and single motor units occurred at intervals, as well as rhythmical trains of potentials (fig. 154). During what appeared to be lightening of sleep induced by particularly cacophonous snores, a single burst of potentials occurred, accompanied by an obvious movement of the eyeball.

Asymmetric Convergence

Asymmetric convergence may be defined as convergence of the eyes occurring in any direction other than along the median

plane. For example, this would occur if an object approached one eye directly from the front. This would require a much greater convergent movement of the other eye to fixate on the approaching object. Breinin (1955) has observed that whenever an eye turned in either a version or a vergence movement there was an increase in the electrical activity of the agonist accompanied by a reciprocal inhibition of the antagonist. When he noted no change in activity in either horizontal rectus of the stationary eye during asymmetric convergence, he concluded that the antagonistic innervations for a version and vergence movement cancelled each other in the brain and never reached the muscles. If the motor impulse to that eye were to change, it would have to move. However, fixation precludes such movement. Miller (1959) seems to agree. He found that sudden asymmetric convergence is accompanied by a burst in the yoke muscles (i.e., pairs of muscles which are agonists in performing versions) followed by a convergent pattern in both medial recti. No increase in coactivity of horizontal antagonists was found during slow asymmetric convergence on an approaching target until the near point of convergence was approached.

An electromyographic study by Blodi and Van Allen (1957) also agrees with that of Breinin. They found that there was no change in the electrical potentials from the horizontal muscles of the apparently stationary eye during asymmetric convergence. They also suggested that the sum total of innervation of the two horizontal muscles has to remain the same regardless of the position of the eye.

On the other hand, Tamler, Jampolsky and Marg (1958) have presented electromyographic data which support Hering's concept of peripheral receipt and adjustment of opposing stimuli to the apparently stationary eye during asymmetric convergence. According to them, the reason the eye remains stationary is due to cocontraction of opposing horizontal recti, that is, there is a simultaneous increase in innervation of the lateral and medial rectus muscles. One possible reason why other investigators have not found this by electromyography was, they suggest, a failure

to induce a sufficient amount of angular convergence in the moving eye in order to register observable changes on the electromyogram of the stationary eye.

Hering's law appears to be supported by both of two test methods of asymmetric convergence. The first is that of smooth, binocular convergence along the axis of one eye; and the second is that of uncovering one eye to force a fusional convergent movement while the other eye continues to fixate.

In "breaking fusion" Tamler *et al.* often found simultaneous decrease in innervation of the horizontal recti of the stationary eye. They explain that if it did not occur, then continued refusion movements with repeated covering and uncovering of an eye would cause greater and greater build-up of electrical activity in the horizontal muscles of the stationary eye.

Blodi and Van Allen (1960) finally laid to rest the theory that vergence movements by the medial recti were somehow controlled by the sympathetic nervous system. After anesthetizing the cervical sympathetic trunk in human subjects, they found no electromyographic change and no directly observable change from the normal response of convergence on command.

Cocontraction

Cocontraction as applied to extraocular muscles (as with synergists in other skeletal muscles) is defined as the simultaneous increased contraction of extraocular muscles which are normally antagonistic in their primary field of action. One suggestion has been that cocontraction occurs when the eye moves from its primary position to any secondary or tertiary position. According to this hypothesis, as the lateral rectus abducts an eye, the vertical recti as well as the superior and inferior obliques cocontract to steady the eye in its horizontal path. At the same time, the cocontraction is believed to prevent undue torsion of the globe and perhaps helps to maintain the abduction because the lateral rectus loses its mechanical advantage as the movement progresses. The same reasoning would apply to adduction, supraduction and infraduction (Tamler, Marg, Jampolsky and Nawratski, 1959).

Tamler, Marg and Jampolsky (1959) studied the electrical
activity of four extraocular muscles simultaneously in many sub-
jects. They concluded that there is little or no increased coactivity
of auxiliary extraocular muscles in adduction, abduction, supra-
duction and infraduction during slow, vertical and horizontal
following movements in planes through the primary position (fig.
155). This does not necessarily mean that they do not contribute
to the movement. Apparently, the effect of muscle activity on eye
movement depends upon the position of the eye at that particular
moment. Hence, they suggest that the "primary position in-
nervational tonus" of the auxiliary muscles, which does not ap-
pear to change during these movements, may indeed contribute
to the movement after the eye has gone a certain distance. Also.
the primary position tonus may be all that is necessary to steady
the eye and prevent torsion during the movement. Tamler and
his group conclude that though one can deduce muscle contraction
with certainty from the electrical activity of a muscle, one cannot
firmly state the function of the muscle at that moment.

Furthermore, they insist that normal muscle activity, as found
in the primary position, is present in the auxiliary muscles during
movement, but that systematic changes in coactivity do not
generally occur. Occasionally, they did find barely perceptible
changes in the recordings from those muscles which are auxiliary
during movements. These changes, when elicited, had no system-
atic pattern and therefore are not consistent with a cocontraction
hypothesis that requires systematic changes with a given direction
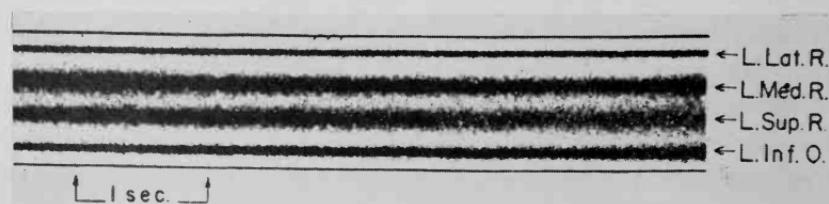
FIG. 155. EMG's from various muscles of "up gaze" in sagittal plane
of left eye. No obvious change in lateral and medial recti. (From Tamler
et al., 1959.)

of movement. Therefore, these authors, whom I have quoted so extensively, are in basic agreement with Breinin's conclusion regarding the same problem.

Stretch and Proprioceptive Effects

Sears, Teasdall and Stone (1959) were concerned about the proprioceptive function of the tension in the extraocular muscles. Previously, muscle spindles had been observed in the muscles of the eye by Cooper and Daniel (1949).

Sears *et al.* investigated by electromyography the possible existence of stretch mechanisms in human extraocular muscles using patients prior to surgical enucleation of the eye. Under topical anesthesia they inserted a concentric needle electrode into one of the horizontal recti muscles. Recordings were made with the eyes both in primary and in horizontal gaze, the latter about 30° beyond the midline. A suture was placed through the tendon of one horizontal rectus muscle which was then cut away from its insertion distal to this ligature. The effects of disinsertion and of gentle manual pulling on the suture were recorded from the agonist muscle, while the muscle was acting as either agonist, antagonist or yoke muscle. With the eyes in primary gaze, they found that the action potentials were unchanged by disinsertion or manual pull. During agonist contraction, however, stretch of the agonist itself, of the antagonist or of the yoke muscle produced a decrease in the frequency and amplitude of the discharges. This inhibitory effect was not observed in a patient with oculomotor palsy when stretch was applied to the muscles of an eye which had a previous retrobulbar alcohol injection.

We can only agree with Sears and his colleagues that probably the extraocular muscles of man do have receptors which can be stimulated by passive stretch. Breinin (1957a) reached the same conclusion, stating: ". . . it appears that a proprioceptive mechanism must be postulated for the extraocular muscles. It is not implied that such a mechanism provides muscle position sense or awareness. Failure to make this distinction has resulted in confusion in the past."

Eyelids

Björk and Kugelberg (1953) have performed the definitive studies on the levator palpebrae superioris and orbicularis oculi. They found the levator to be continually active during waking hours except when looking sharply downwards or when the eyes are closed. Lowering of the upper lid is accompanied by progressive decrease in levator activity but with little or no activity in the orbicularis. In other words, the lid is lowered passively by the relaxing of the levator. The lowering of the lid in the act of blinking, however, is caused by activity in orbicularis with immediate cessation of activity in the levator (fig. 156). This is followed immediately by the reverse (inhibition of orbicularis and activity in levator).

Blinking was also studied by Van Allen and Blodi (1962). They too found a quick, well-controlled, reciprocal relationship between the orbicularis oculi and levator palpebrae superioris. This occurred as expected in normal people, but it also was preserved in the presence of gross neurological conditions affecting the region.
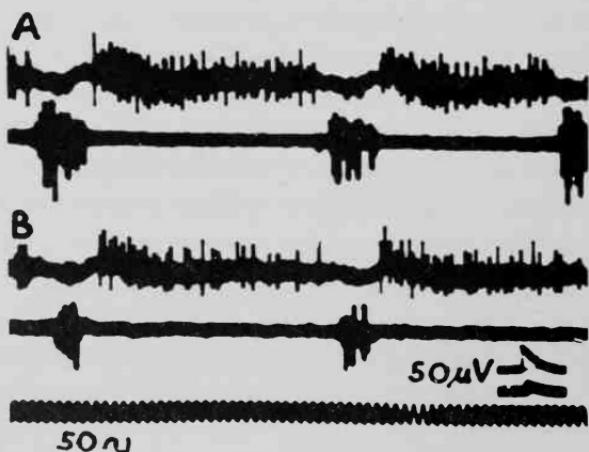
FIG. 156. *A*, EMG's of blinking from levator palpebrae superioris (*upper trace*) and orbicularis oculi. *B*, spontaneous blinking. (From Björk and Kugelberg, 1953.)

In view of the indecision surrounding the innervation of the levator palpebrae and arising from the drooping or ptosis of the lid that is part of Horner's syndrome, Blodi and Van Allen (1960) investigated this muscle further. Duplicating a Horner's syndrome by producing a block in the cervical sympathetic trunk with local anesthetic, they found no significant effect on the levator. Even with marked ptosis of the upper lid, the activity in levator was not reduced. Blodi and Van Allen also found normal EMG's in the levators of patients with long-standing Horner's syndrome. Therefore, taking all this together, we must conclude that the sympathetic nervous system does not innervate the striated levator palpebrae. The drooping of the lids in Horner's syndrome is not due to any direct paralytic effect on the striated fibres but appears to be due to paralysis of smooth muscle.

Muscles of the Middle Ear

As the reader would suspect, the tiny stapedius and tensor tympani muscles have not been studied extensively. However, Berlendis and De Caro (1955) in Italy, and more recently Wersäll (1958) in Stockholm, Kirikae (1960) of Tokyo, Carmel and Starr (1963) of Bethesda, U.S.A., Dewson et al. (1965) at Stanford University and Henson (1965) at Yale have performed EMG's within the middle ear of experimental animals. In Copenhagen, Salomon and Starr (1963) have made direct recordings from two human patients. But most studies of tensor tympani and stapedius in man have been made by an ingenious *indirect* method now gaining fairly wide acceptance. This depends on measurements of changes in acoustic impedance in the external ear canal. Interested readers should consult Møller (1961) for a technical description.

Wersäll's beautiful experiments, which were performed on rabbits and cats and described in his monograph, established several important points. He showed that there is continuous activity at rest, i.e., resting tonus, in these middle ear muscles. When sound reaches the eardrum there is a small delay (less than 0.1 second) before a reflex contraction of the muscles becomes evi-

dent. This delay is constant regardless of the intensity of the sound. There is however a threshold above which the sound must rise to elicit the reflex. It is generally higher in the tensor tympani than the stapedius. Nonetheless, contrary to widely held opinion, protective action against sudden loud noises is no more developed than against a moderate noise.

Wersäll showed a characteristic difference between the two muscles in the dependence of reflex tension on sound intensity. Stapedius, but not tensor tympani, reaches a plateau before the sound is so intense as to become injurious. Under the stimulation of steady sound the reflex contractions of both muscles often showed undulatory fluctuations. During strong sustained stimulation, the tension drops to a steady state in both muscles. Wersäll ascribed this fall in tension to fatigue.

Kirikae (1960) measured the latency of the acoustic reflex more precisely than Wersäll. For stapedius it was 3.4 msec and is shorter than it is for tensor. Activating time, which requires muscle contraction, is 2 to 3 msec. Maximal contraction takes a further several msecs. Fatigue or adaption phenomenon was also prominent in his studies.

In unrestrained cats, Carmel and Starr (1963) added a number of new observations or confirmed Wersäll's findings. As in his investigation, the middle-ear muscles were found to relax gradually during prolonged sound stimulation. Both muscles contract during certain bodily movements and vocalization. Reflexes are modified by previous exposure to loud noises. Application of electric shock concurrently with test signals also modifies the responses of the muscles. Thus they concluded that a wide variety of dynamic processes influence the activity of middle-ear muscles, not just the physical characteristics of sound impinging on the ear.

The limited studies on man reported by Salomon and Starr (1963) revealed the middle-ear muscles to be active with general motor events, such as closing the eyes, movements of the face and head, vocalization, yawning, swallowing, coughing and laughing. Thus they proposed the theory that central controls for

these functions are closely integrated. Dewson *et al.* (1965) found (in cats) a close similarity or relationship in the emg reaction of the middle-ear muscles and the stage of rapid eye movements during sleep.

The activity and function of middle-ear muscles in echolocating bats forms the subject of an intriguing paper by O. W. Henson (1965). He found that stapedius begins to contract just before vocalization and reaches its maximum as each pulse begins, apparently to dampen the ossicles during the sound-emission stage. Relaxation starts immediately and continues during the echo phase, apparently to allow its maximum perception. Tensor tympani seems to play no part in this system.
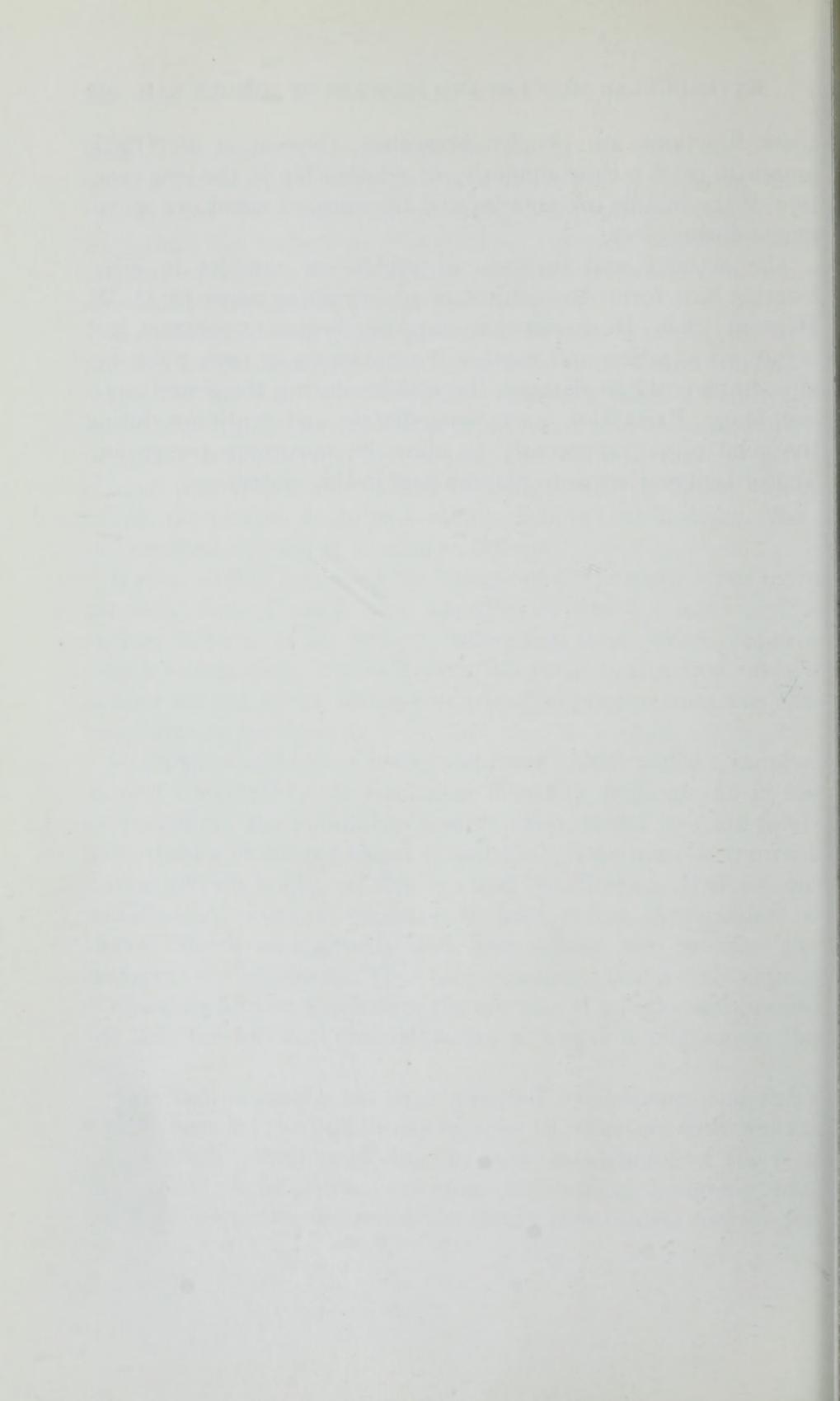
CHAPTER *19*

The Future of "Non-Clinical" Electromyography

ELECTROMYOGRAPHY fulfils a real need in diagnostic or clinical examinations and it will thrive in the large and medium sized medical centres around the world. My concern in this final chapter is not with clinical electromyography; rather, it is with basic scientific electromyography of the type which has occupied our attention in the previous chapters. What directions will such investigations take—or, indeed, should they take?

First of all, we should abandon any idea that this is a technique that needs to go looking for a job. We must agree that it is a technique standing ready to be called upon whenever problems present themselves. Do such problems still exist or are they all solved?

To answer these questions we should review the various parts of the musculature and draw attention to functions which are at present inadequately explained, particularly those which are the subject of great controversy, and, finally, those which are the richest in dogma. In all three categories there are problems that

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cry out for solution by electromyography. Almost every page of this book illustrates how many problems have been solved while still others have been left unsolved. Any anatomist, physiologist, kinesiologist or orthopedic surgeon can point out many such unsolved problems.

TECHNIQUE. As suggested in Chapter 2, a general improvement in technique is needed. Reliance on the exclusive use of surface electrodes must be abandoned by electromyographers who hope to add to the future of electromyography. Adequate apparatus and training are now quite readily available. Therefore, research in electromyography should be improved in quality and reliability. Improved techniques for synchronized photographic recording of movements, such as those of Hardy (1959), should be adopted more widely.

FATIGUE AND NEURO-MUSCULAR STUDIES. Though electromyography has produced some useful results there is enough conflict—as revealed in Chapter 4—to make a final verdict on the mechanisms of fatigue impossible. An attack on a broader front is required; and when it is made electromyography will be the main factor in its success. The recent awakening of physical-training specialists to the possibilities of electromyographic evaluation raises the question of the direction their interest will take. If they do not avoid the pseudo-scientific approach which often is the curse of studies in athletics, they will get so few valid results from electromyography that they will only succeed in casting unwarranted suspicion upon the technique.

CONTROL AND TRAINING OF MOTOR UNITS. Being deeply involved in our laboratory in this special study, my colleagues and I are convinced of its fundamental importance. Widespread employment of our techniques can only lead to many useful applications, not the least of which is the control of myoelectric devices for the handicapped.

MUSCLE MECHANICS. Anatomists and physiologists in particular are faced with the solution of problems, both large and small, many of which eventually have practical implications. These problems very often will have arisen from purely clinical prob-

lems. Therefore, in view of this mutual exchange, co-operation between research staffs and clinicians is especially needed in this sphere.

POSTURE. The disagreements described in Chapter 8 about the rôles of various postural muscles is not a reflection on the value of electromyography. It is, however, an indication of the lack of enough confirmation. All too often, opposite opinions are based on short unconfirmed series. Obviously, then, we must expect— indeed, demand—further unbiased confirmation by independent groups of all the opinions now available. Certainly, the genuine scientist welcomes a critical repetition of his work. Although he does not like to see it capriciously questioned or slighted, he respects an honest and careful evaluation.

UPPER AND LOWER LIMBS. Looking back over Chapters 9 to 11, I am impressed with how almost all of the emg studies on the limbs are scattered and unrelated. Many have been done with very special problems in mind, but only a few have been systematic. Fewer still have had adequate confirmation. Finally, the hand and foot have been unaccountably neglected. The future needs in the limb regions, therefore, are self-evident.

THE BACK. Although there has been an excellent cross-confirmation of the basic principles governing the action of back muscles, the finer function of the intrinsic muscles has been ignored. Clinical problems, such as the etiology of scoliosis, require solutions that electromyography can help provide.

GAIT. As pointed out in Chapter 13 on Locomotion this is a fruitful field of study, but it requires unusually complex apparatus. Fortunately a number of laboratories are embarked on full-scale studies of this practical type of work.

ABDOMINAL WALL AND PERINEUM. Almost all the emg work done on the anterior abdominal wall and the sphincters of the urethra and anus require confirmation. The levator ani remains completely ignored though it is of great importance and not entirely inaccessible.

RESPIRATORY MUSCLES. Although in recent years much excellent work has been reported on the intercostal muscles, these

studies have been isolated and are often conflicting. Much of this work requires confirmation with needle electrodes before complete acceptance can be expected. Work on the diaphragm of real practical value is now started but will require considerable new effort.

PHARYNX AND MOUTH. Although some electromyography of the swallowing mechanisms has been done recently, much additional work is needed with many novel approaches and a variety of techniques. Clinicians working closely as partners with experienced electromyographers are the best qualified to broaden our knowledge. The tongue is almost a complete no-man's-land as far as electromyography is concerned, and almost any investigator with an interest in the tongue is confronted with a minimum of technical problems.

LARYNX. Anyone reviewing the literature of this region will be satisfied that the heated controversy has shed limited light on the true functions of the muscles of the vocal cord. The various opposed views cannot be reconciled. Here, too, several different approaches are needed and the best results will come again from teams of experienced clinicians working imaginatively with experienced electromyographers. Neither group of specialists can operate successfully without the other.

MUSCLES OF MASTICATION. In recent years there has been an unfortunate lack of significant new publications on the electromyography of the mandibular muscles. A glance at Chapter 17 will reveal that a particular divergent opinion is supported only by the experiments of the author of that opinion. Though clinical dental electromyography is still enjoying the dregs of several vintage years, it can only provide valid results if the basic physiology is well grounded. Indeed, practising dentists are likely to turn away from electromyography completely unless a solid basis of normal electromyography is made available.

FACE AND NECK. The muscles of expression, the infrahyoid muscles and the suprahyoid muscles of the floor of the mouth are are virtually virgin territories for electromyographic exploration. Their neglect is particularly puzzling in view of their relative

accessibility. The very vital rôle of the scalenes in respiration is of such great importance that it is rather amazing how little attention has been paid to them except by a handful of investigators.

MUSCLES OF THE EYE AND MIDDLE EAR. These regions must be investigated by specialists. We are fortunate that a considerable number of ophthalmologists have been involved in electromyography. However, the vigorous controversies that have resulted appear to have alienated many other ophthalmologists. Undoubtedly, with the expenditure of time and effort, truth will emerge. There can be little doubt that electromyography provides great promise in the practical problems of eye movements. The muscles of the middle ear in the human being remain uninvestigated. Here again, judicious team-work between a clinical specialist and an electromyographer would provide fascinating and rewarding results.

ENVOY. These, then, are some of the problems of the future in normal or "non-clinical" electromyography. Patience and persistence combined with flair and imagination will be needed. Little of real value comes easily in science. In this field, where one must apply the techniques of one science to the solution of problems in others, the need for all these ingredients is especially acute. In the final analysis, the future of electromyography is exciting and real especially for those who are adequately equipped and trained.
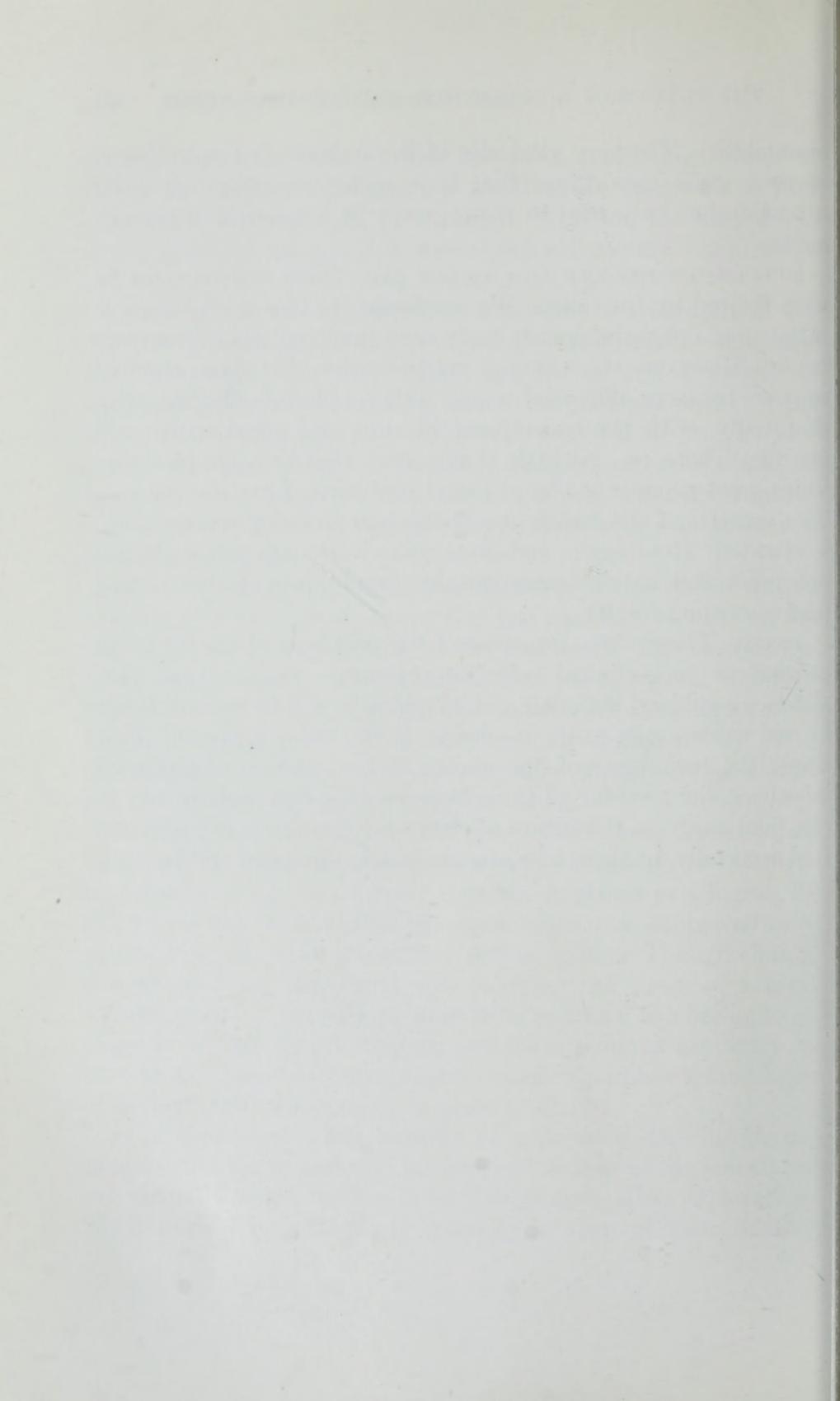
Appendix
Some Useful Commercial
Equipment*

This appendix is only a simple guide for a minority of readers. As such, it is not a complete account of all the apparatus available; that would fill a book. However, inquiries often arise about the appropriateness and availability of various electronic systems. The following paragraphs are a summary of the sort of preliminary advice one gives. Finally, under the heading of "a basic set-up" (p. 367) a brief account is given of how to use inexpensive apparatus (less than $1,000) to make a start in EMG.

Commercial EMG's

The Medcraft Model M2 Electromyograph (fig. 157) presents a complete, compact, two-channel instrument housed in a steel console mounted on swivel casters. It comprises all of the elements usually found in laboratory equipment, namely: a high discrimination preamplifier, a stable wide range power amplifier, a high fidelity speaker system and a cathode-ray oscilloscope. The following description is based on the information provided by the manufacturer.

Each element of Medcraft M2 is furnished in duplicate, providing a two-channel system. In addition, a two-channel frequency-modulated tape recorder and a two-channel inkwriting

* This appendix was prepared with the help and advice of my colleague and chief electronic technologist, Mr. Glenn Shine.
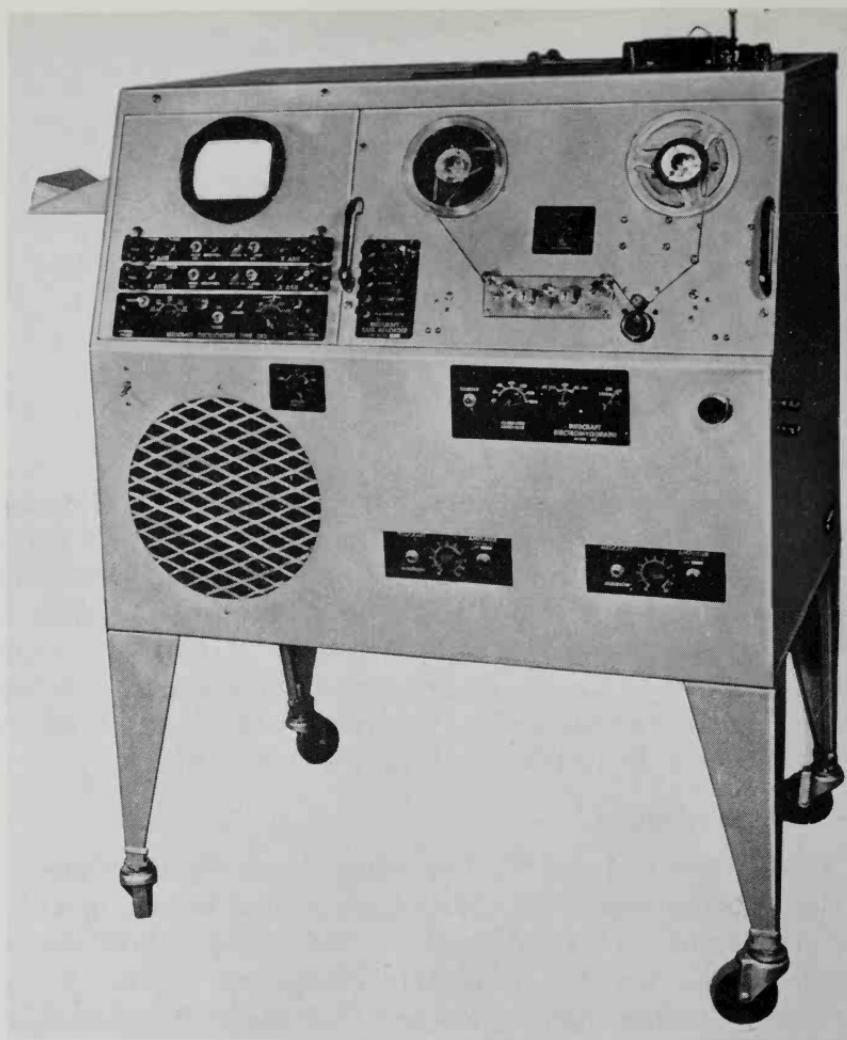
FIG. 157. Medcraft electromyograph model M2. (Photo by Riviera; through courtesy of manufacturer.)

recorder are included, so that phenomena may be preserved on magnetic tape or as a graphic record. Finally, provision is made to play the magnetic tape record back at $\frac{1}{20}$ the original speed, so that a graphic record of the phenomena is immediately available on a scale giving 1.2 mm per msec (approximately 4 feet per

second), a resolution capable of presenting any myographic phenomena in sufficient detail for accurate analysis.

The input control circuit contains an input switch which places the input terminals, an A.C. calibrating network, or a D.C. calibrating network on the input of the two preamplifiers. The preamplifier is a complete, single stage differential unit which provides, in conjunction with the differential action of the first stage of the power amplifier, a rejection of not less than 15,000 to 1, and, with careful selection of tubes, as high as 30,000 to 1.

The power amplifier consists of three sections: (1) An amplifier designed to accept the output of the preamplifier and feed the oscilloscope, the inkwriting recorder and the speaker amplifier. Provision is also made to feed a microphone into the power amplifier; (2) an oscillator-frequency modulator system which feeds the magnetic tape recorder; and (3) a demodulator-amplifier which feeds the output of the tape recorder back into the power amplifier.

The oscilloscope is a two-beam conventional unit employing a two-gun cathode-ray tube. The speaker amplifier provides high quality audio response from the signals amplified by the power amplifier. The tape recorder is a specially designed unit provided with both a one-to-one and twenty-to-one playback ratio. The inkwriting recorder is a conventional unit as used in standard electroencephalographs.

Accessories include: (1) an inexpensive camera and mounting hood; (2) a camera providing automatic film advance for rapid exposure techniques (Robot Starr 35 mm with 2.8 lens, x-synchronization shutter and lens adjusted for proper focus).

The Medcraft Model M-1 Electromyograph is a smaller, portable, self-contained instrument, comprising a high-rejection preamplifier, high quality broad-band power amplifier, oscilloscope and speaker (fig. 158). The preamplifier is a single-stage differential unit providing, in conjunction with the differential action of the first stage of the power amplifier, a rejection of common mode signals in a ratio of 20,000 to 1.

The power amplifier is a wide range unit with a gain control

Fig. 158. Medcraft portable electromyograph, model M-1. (Photo by Riviera; through courtesy of manufacturer.)

capable of accepting the output of the preamplifier and driving the speaker and the oscilloscope amplifier. The speaker is a standard heavy-duty permanent-magnet unit providing a broad frequency response and mounted in an arrangement to reduce feedback. A volume control for this speaker is provided on the front panel.

The EMG produced by the Meditron Co. and used widely in clinical investigations is a dual-channel instrument with display on a 5-inch cathode-ray tube. A model more recent than the one illustrated in figure 159 is Model 302. Its vertical amplifiers have an input impedance of 10 megohms grid to grid, and a common mode rejection ratio of 7000 to 1 at 60 cps (Hz), with an unbalanced 5 Kohm and 10 Kohm source impedance. The rejection ratio is approximately 100,000 to 1 at 60 Hz for zero source impedance, but the emg signal does not have zero or balanced

Fig. 159. Meditron electromyograph model 201A-1: console type with tape recorder. (Photo through courtesy of manufacturer.)

source impedances. Noise level is approximately 2 μv rms (10 μv peak to peak) over a 10 Khz bandwidth. The frequency response is from 15 to 10,000 Hz with adjustable high frequency roll off. A calibrated attenuator allows convenient switching to any of 8 sensitivity settings (20 to 5,000 μv per inch). An audio-amplifier and speaker are incorporated in the cabinet for monitoring inputs separately or in combination. A nerve stimulator with a choice of pulse width and a muscle-stimulator for verifying precise electrode placement are also incorporated. Either a Polaroid camera or a 35 mm camera is used for photographing the face of the cathode-ray tube. An accessory tape recorder is also available.

Two single-channel Meditron units are also available. Model 312 is similar to the one just described, and Model 301 is a small portable unit.

The Teca Corporation of White Plains, New York, produces two excellent EMG models. The Teca Model B is a compact one-channel instrument with facilities for electromyography and studies of nerve conduction time. It includes a loudspeaker for aural monitoring and a synchronized Polaroid camera for recording the patterns displayed on the 7-inch screen of the cathode-ray tube.

The Teca TE Series, in addition to including the Model B features, are more comprehensive one- or two-channel systems assembled in consoles, and they provide flexibility in the choice of optional apparatus (fig. 160). The two-channel magnetic tape recorder which is part of this system is automatic in operation and is especially designed with extended low-frequency response to permit accurate rendition of the motor unit potentials on the cathode-ray tube during playback. The tape recorder is designed as an integral part of the system and therefore does not require any special additional controls for operation.

Sensitive, stable differential amplifiers with high input impedance, low input-noise level and wide frequency response are used. High frequency cutoff filters in the amplifiers can selectively restrict the frequency response when using skin surface electrodes

Fig. 160. The TE2-7 two-channel console-type electromyograph. (Photo through courtesy of manufacturer.)

and at other times when wide dynamic response is not required. In addition, rejection filters may be switched in to remove power line ("60 cycle") frequency artifact when necessary. Integrators can be supplied by the manufacturer as part of the amplifiers for recording integrated electromyograms.

The European-made DISA Electromyograph has three independent amplifier circuits, which therefore pick up action potentials from three sites simultaneously. This electromyograph (Type
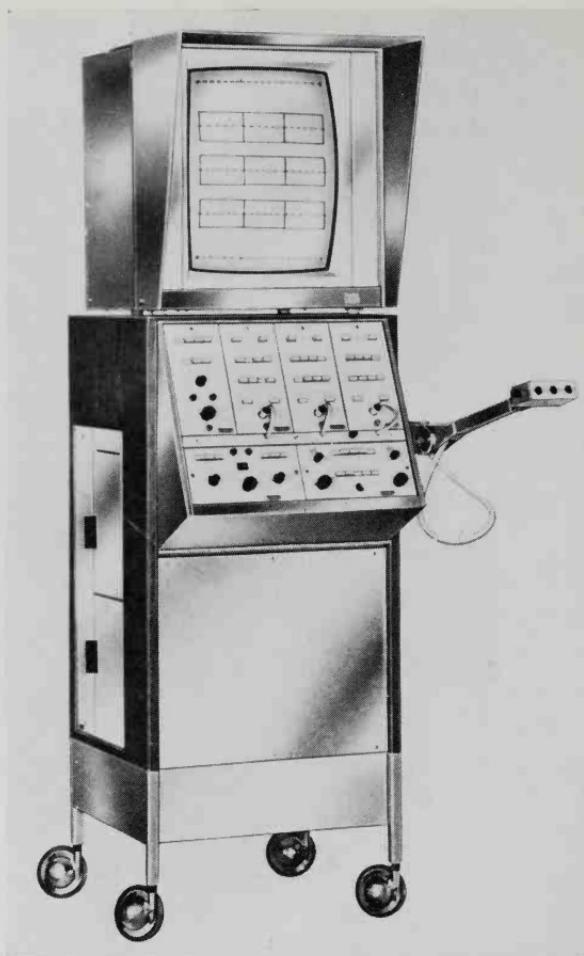
Fig. 161. The DISA electromyograph, Type 14A30. (Photo through courtesy of manufacturer.)

14A30) is manufactured in Denmark. It is designed for both routine clinical examination and pure research. The monitor is a 19-inch, TV-type picture-tube with a medium persistence phosphor screen for ease in viewing (fig. 161).

The differential vertical amplifiers have an input impedance of 200 megohms (balanced) shunted by 15 pf (picafarads). Noise

level, with the input shorted, is 1.5 μv rms over a bandwidth of 10,000 Hz. The common mode rejection ratio, using a concentric needle electrode, is 50 db minimum. The frequency response of the amplifiers can be adjusted, in that the high frequency cutoff can be set to 10,000 or 1,000 Hz and the low frequency cutoff set to 2 or 20 Hz. A 16-step attenuator provides sensitivities ranging from 5 μv per division to 30 mv per division as viewed on the cathode-ray-tube monitor.

The camera unit consists of three 1.5-inch cathode-ray tubes on which the signals from the three emg amplifiers are traced. Photographic paper, 10 cm wide, is used for recording. Markings and text (i.e., patient's name) may also be recorded on the paper. Several modes of operation of the camera are possible, including continuous paper feed and single-shot recording. An audio amplifier and speaker permit monitoring of the signal, channel by channel. An accessory stimulator is available for nerve or muscle stimulation.

The Italian-made three-channel Galileo Electromyograph is also used in Europe and has many of the same virtues as the above instrument. In addition, its frequency response can be changed by a selective switch so that EEG's and ECG's can be also picked up. (For a detailed description of the DISA and Galileo Electromyographs, see Serra and Covello, 1959.)

The past years have seen a vigorous invasion of the world market by electromedical apparatus of Japanese design and manufacture. Though we have not yet worked with such equipment (except for the excellent Hitachi electron microscope), we expect that they will be quite acceptable.

The Sanborn Division of Hewlett-Packard of Waltham, Mass., and the Spinco Division of Beckman Instruments Inc. of Palo Alto, Calif., both produce excellent diversified lines of complex electronic apparatus suitable for multi-channel emg recordings. These are widely used in many applications. It is difficult to describe in a few words the many possibilities offered by the elegant equipment available from these manufacturers.
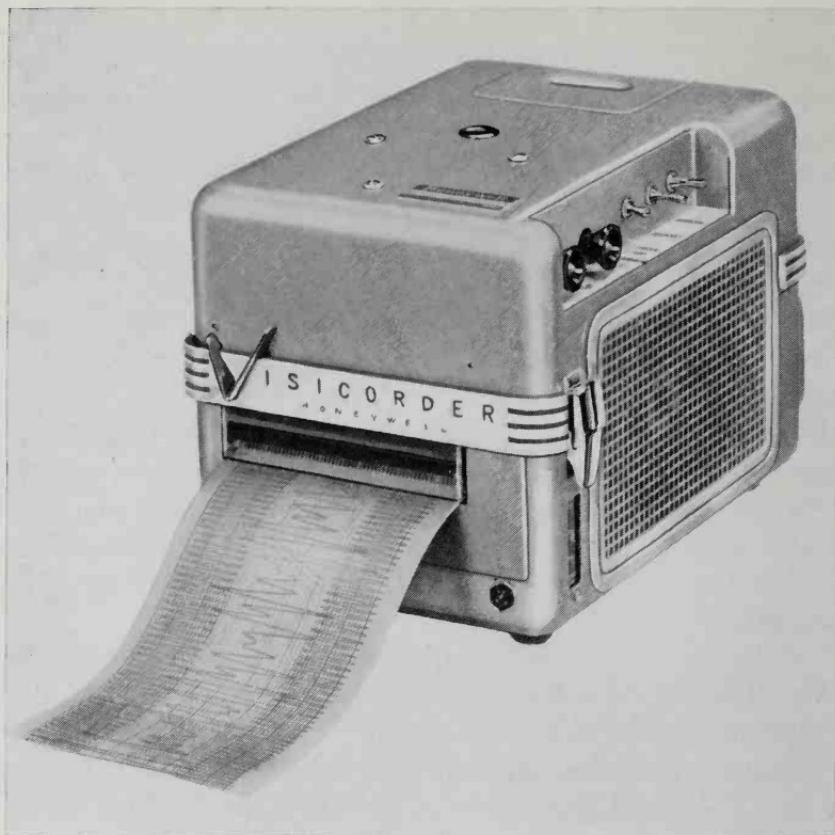
Fig. 162. Visicorder 906-B. (Photo through courtesy of manufacturer.)

The above descriptions do not constitute an exhaustive listing. Other excellent commercial equipment is now available on the market at a wide range of prices.

Direct Recorders

Several companies are producing direct read-out recorders that use an ultra-violet light source and sensitive paper. The Honeywell line of "Visicorder" is available with as many as 36 channels or as few as 6 (fig. 162). Miniature galvanometers having a frequency response to 4800 Hz are used to deflect the light beams onto the moving paper. Among others, a galvanometer with a response of 1000 Hz is available; this is good for most emg applications.

The galvanometers may be set to produce a trace on any portion of the paper. The individual tracings are momentarily interrupted to facilitate identification of individual channels; this is especially valuable when many tracings cross one another while recording. Model 1612 can record up to 36 channels of information on sensitized paper 12 inches wide. Amplifiers for use with the various Visicorders are available from Honeywell: the Accudata 108 A.C. Amplifier and 109 D.C. Amplifier. These two must be used in series for proper drive of the fluid-damped galvanometers in the Visicorder. Characteristics (input impedance, gain, rejection ratio, etc.) are similar to other preamplifiers described above.

A small (15 pound) 6-channel direct recorder is also available from Century Electronics and Instruments of Tulsa, Oklahoma. This unit, model 444, produces grid and timing lines and has 4 recording speeds. Galvanometers with a frequency response to 2000 Hz are available.

Linagraph Cameras

To record emg signals from the face of a cathode-ray tube on photographic film (or paper) requires some form of camera. The most useful type is the linagraph camera that uses long rolls of 35 mm film (up to 100 feet) for lengthy recording of signals as linear tracings. We have found the Cossor Oscillograph Camera, Model 1428 (made in London, England, by Cossor Instruments, Ltd) particularly valuable.

This is a versatile, low-cost instrument. The film is moved at various set speeds behind the open aperture, recording the cathode-ray spot or spots as a continuous line or lines. Each spot has no x-axis deviation (i.e., the horizontal sweep is stopped). Thus the time base is provided by the regulated horizontal movement of the film. This can be varied in steps from .05 to 25 inches per sec.

A Basic Set-Up

Even without the standard emg units described in the earlier paragraphs, good results can be obtained with readily available

and inexpensive commercial equipment designed for other general uses. For example, in certain projects one might need only a minimal set-up. We often rely on a cheap single-channel assembly consisting of a Tektronix Oscilloscope (Type 502), a Tektronix Low Level Preamplifier (Type 122) and a Heathkit Audio-amplifier (Type A-9C) with an ordinary loudspeaker. Equivalent units of other manufacturers can be and are substituted. For example, the preamplifier might be an Argonaut Type LRA-042 or a Sanborn Type 350, etc. Many inexpensive general-purpose oscilloscopes could be substituted for the Tektronix 502 for visual display. One should aim for a minimum sensitivity of about 25 μv per inch.

Small audio or hi-fi amplifiers (using either transistors or tubes) are readily available. They can be satisfactory if they have a power output of about 3 watts (this is not critical) and provision for magnetic phono input. They can be connected to the output of the preamplifier for audio monitoring in conjunction with a standard loudspeaker. A start can be made in electromyography without spending huge sums of money. Further, the simple assemblies will still be useful as adjuncts when more elaborate and comprehensive apparatus has been obtained.

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